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HOT CARRIER RELAXATION AND RECOMBINATION IN GaSb/AlSb QUANTUM WELLS

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ABSTRACT

We present picosecond time-resolved experiments on GaSb/AlSb quantum wells using a sum frequency generation technique. Recombination processes as well as relaxation and cooling processes of hot carriers in 2D GaSb/AlSb systems are studied. As a result, we find LO-phonon scattering times τ_{LO} of about 12ps.

KEYWORDS

Hot carrier cooling; reduced carrier phonon interaction; recombination processes; psec experiments with GaSb/AlSb quantum wells.

Recently the investigations of picosecond phenomena in semiconductors have attracted great interest, especially the behaviour of hot carrier dynamics in 2D semiconductor structures. In this paper we present picosecond investigations of GaSb/AlSb quantum wells with well widths between 5nm and 11.5nm. Recombination mechanisms as well as cooling of hot carriers are studied and compared to theoretical expectations. Concerning the hot carrier relaxation in 2D structures, it has been shown previously by Ryan and others (1984), by Shah and others (1985) for GaAs quantum wells and by Xu and Tang (1984) for InGaAs quantum wells, that the carrier cooling rate in 2D- systems is extremly smaller than expected theoretically. Mainly hot phonons are responsible for this reduced carrier phonon interaction. This behaviour of the reduced electron-phonon interaction in 2D systems is confirmed in our experiments in GaSb/AlSb quantum well structures from the evaluation of the carrier temperature T_c versus time delay.

The experiments have been performed in GaSb/AlSb samples grown by MBE (Griffiths, Kroemer and others, 1983) with GaSb well thicknesses from 5nm up to 11.5nm. For the excitation of the samples we used a mode-locked Nd-YAG laser at a wavelength of 1064nm with a repetition rate of 100MHz. The FWHM of the pulses was approximately 200ps and the average energy was about 1nJ per pulse. With this laser the carriers were excited directly into the GaSb wells, having an excess energy of about 250meV compared to the subband edge. To detect the luminescence of the samples with emission wavelengths between 1.3μm and 1.5μm we generated the sum frequency of the luminescence and the laser with a nonlinear $LiJO_3$ crystal. The length of the crystal is 15mm with an angle of 25^o to the optical axis and the phase matching was achieved by angle tuning. The advantages of the up-conversion technique used in our experiments are the high dynamical range of more than 4 decades of the detected luminescence decay, the time resolution via delay lines and the possibility of single photon counting with a high sensitive GaAs photomultiplier in the visible region (around 600nm). In principle, the time resolution is only limited by the optical pathlength of the light in the nonlinear crystal. Actually we could achieve a time resolution of about 50ps limited by the laser pulses. We used this up-conversion technique to study the recombination mechanisms and the cooling processes of hot carriers in GaSb/AlSb quantum wells.

To investigate the dynamics of extrinsic and intrinsic recombination processes, we recorded transient spectra at different time delays. The spectra taken directly after the laser excitation (in the first 100ps), show emission lines having their maximum intensity about 8meV higher than spectra recorded at several hundred picoseconds after excitation. This transient energy shift of the emission is due to a change from free carrier recombination to band acceptor recombination (GaSb is unintentionally p-doped). At high carrier densities, the band acceptor transition saturates and the free carrier recombination dominates the emission.

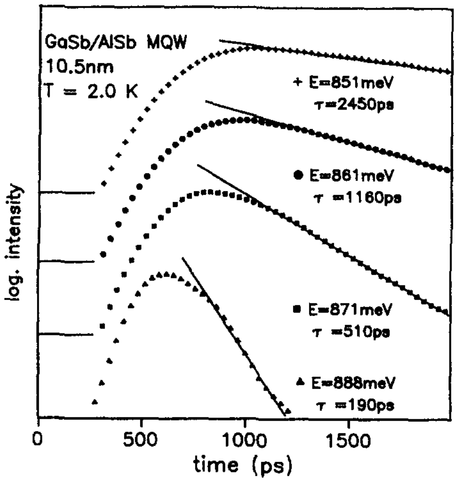

Fig. 1. Decay times for a 10.5nm sample for different energetic positions

This is confirmed by the dependence of the carrier life times at different energetic positions, which is shown in Fig. 1, for a sample with 10.5nm. As expected from the observed energetic shift with time, the emission line is composed of two recombination channels which have different transient behaviour. For the maximum of the emission at about 860 meV the time constant is about 1ns. At the high energy part of the emission line (888 meV) carriers recombine with time constants of about 190ps which indicates the rapid cooling of the hot carriers. At the low energy part of the emission, recombination life time increases drastically up to 2.5ns. In addition to the above described line shift in the transient spectra, this is consistent with a change from free carrier recombination to band acceptor recombination.

In the following we shall discuss the behaviour of the high energy part of the emission lines, which provides information on the hot carriers in the GaSb/AlSb structures. Especially the transient behaviour of the carrier temperature due to carrier phonon interaction is of interest here. Figure 2 gives a set of spectra taken at different time delays after laser excitation (t_0) for a sample with L_z = 10.5 nm. Since the luminescence intensity is proportional to the step-like combined density of states for electrons and holes D(E) and to the electron and hole distribution functions f_e and f_h, respectively and the excess energy of the carriers is very high, we can assume a simple Maxwell-Boltzmann intensity profile for the high energy part of the luminescence:

$$I(E) \sim \exp(-E/kT_c) \qquad (1)$$

where T_c is the carrier temperature. Using equation (1) we can deduce from the slope of the high energy part of the spectra the carrier temperatues T_c for different time delays.

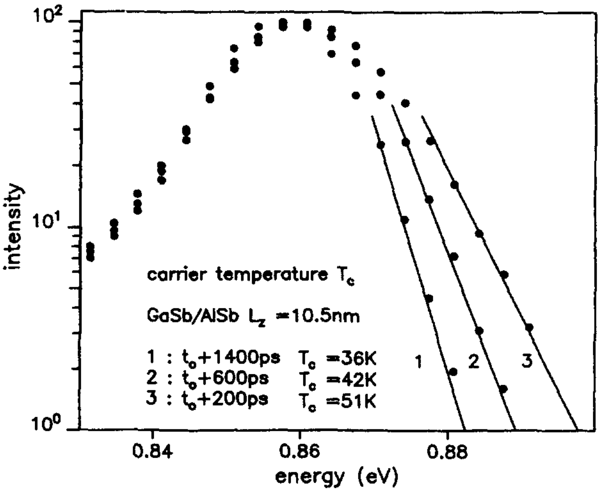

Fig. 2. Determination of the carrier temperature T_c for different time delays after excitation (at t_0)

As shown in Fig. 2, the carrier temperature T_C decreases with increasing time delay, which reflects the cooling of the carrier system. The spectra were recorded at a lattice temperature T_L = 2K. Even for time delays as long as 600ps, the carrier temperature remains higher than 40K, which indicates the slow thermalization of the hot carriers in GaSb quantum wells. Plotting the carrier temperatures versus time delay, one obtains the cooling curve as shown in Fig. 3. The dots are the experimental data (where the first two dots are not reliable, as the laser is still present during the first 100ps of excitation). We find surprisingly low energy loss rates in the GaSb quantum wells of about 1meV/100ps for electrons high up in the subband, down to values of about 0.05meV/100ps at lower energies. To discuss these low energy loss rates, we study the carrier phonon interaction using a theoretical model for the carrier relaxation (curves in Fig. 3) which is described below.

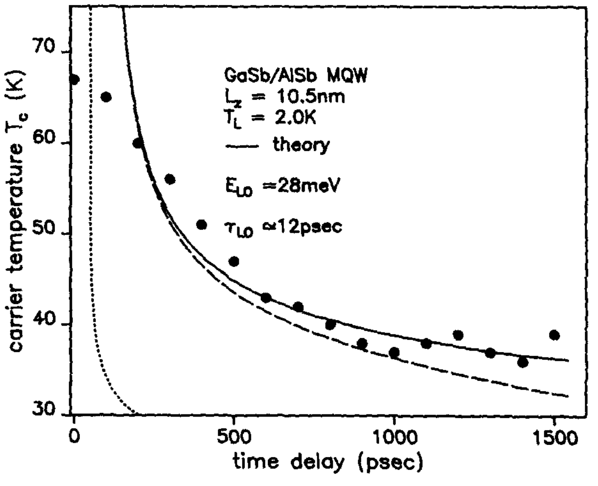

Fig. 3. Carrier cooling curve for a 10.5nm sample; dots: experimental data; curves: theory (see text)

We calculate the energy loss rates, by assuming that at high carrier densities (shortly after excitation), the carrier-carrier interaction takes place on a very short time scale (< 1ps) and a thermal equilibrium distribution of the hot carriers is well established. Furthermore we assume, that the whole excess energy is in the electronic system and that the carrier cooling will mainly take place via the lattice,which is at low temperatures (about 2K). To study the carrier phonon interaction, we evaluate the total energy loss rate $\langle dE/dt \rangle_{total}$ as given by Göbel and Hildebrand (1978):

$$\left\langle \frac{dE}{dt} \right\rangle_{total} = \left\langle \frac{dE}{dt} \right\rangle_{LO} + \left\langle \frac{dE}{dt} \right\rangle_{PE} + \left\langle \frac{dE}{dt} \right\rangle_{DP} \quad (2)$$

The first term gives the cooling of hot carriers via LO-phonons (so called Fröhlich interaction) which is most efficient for carrier temperatures T_C above 40K. The other two terms display the interaction of carriers with acoustic phonons by piezoelectric and deformation potential scattering, respectively. In our calculation we assume that electrons and holes have mainly the same temperature. To calculate the dependence of the carrier temperature versus time, we have to add up all energy losses of the carriers. For non-degenerated electron hole distributions the average energy loss rate per carrier in 2D systems is simply given by $k \cdot dT_C/dt$ and we can write for the carrier temperature resulting from the picosecond excitation:

$$T_C(t) = T_o - \frac{1}{k} \int_o^t \left\langle \frac{dE}{dt} \right\rangle_{total} dt \quad (3)$$

Taking the suitable material parameters for GaSb (which describe the coupling strength between carriers and phonons) we evaluate the total energy loss rates. From this evaluation we expect, that for GaSb the whole energy loss rate is by a factor of 5 smaller than in GaAs or InGaAs systems, which results mainly from the different dielectrical constants and different effective masses. The evaluation of equation (3) using these data, results in a LO-phonon scattering time τ_{LO} = 0.4ps. The dotted line in Fig. 3 shows this situation, but no fit to the data can be achieved. Therefore we reduce the carrier LO-phonon energy loss rate by a factor of about 30, which increases the LO-phonon scattering time τ_{LO} to a value of about 12ps. This situation is shown by the dashed curve in Fig. 3. For temperatures below 40K there is still a deviation between experiment and theory. Therefore we also reduce the energy loss rates for the acoustic phonons by the same amount as for the LO-phonons, which leads to the solid line in Fig. 3. As a result, an agreement between experiment and theory for the cooling of hot carriers in the GaSb quantum wells can be achieved by reducing the energy loss rates for optical phonons as well as for acoustic phonons by a factor of 30 which gives an LO-phonon scattering time of τ_{LO} = 12ps.

This observation is consistent with results given by Ryan (1984) for GaAs quantum wells and by Shum (1986) for InGaAs quantum wells, who find similar high carrier phonon coupling times in their experiments. One reason for the weak carrier cooling might be due to the large carrier density which leads to screening effects and reduces the total phonon emission rate. Yoffa (1981) calculated for GaAs a reduction by a factor of 25 for carrier densities of $10^{18}/cm^3$. This factor decreases with decreasing density, so that screening effects as a reason for smaller energy loss rates seems only be useful for times shortly after excitation, when the carrier density is high enough. A more important reduction of the carrier phonon interaction is due to nonequilibrium phonons, which create a bottleneck for the cooling of hot carriers. Pötz and Kocevar (1983), as well as Price (1985) and Shah (1986) showed that hot phonons which are created by hot carrier cooling and emitting optical phonons will reduce the energy loss rate <dE/dt> substantially and therefore increase the electron LO-phonon coupling time τ_{LO} up to values of about 10ps.

In summary, we have discussed the transient change from free carrier recombination to band acceptor recombination in GaSb/AlSb quantum wells. For the cooling of hot carriers we could show, that carrier phonon interactions for the LO-phonons as well as for the acoustic phonons must be reduced to describe the cooling of hot carriers in GaSb AlSb quantum wells. We find a carrier LO-phonon scattering time τ_{LO} = 12ps for this system.

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