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Nonequilibrium Phonon Effects on the Time-Dependent Relaxation of Hot Carriers in GaAs MQW

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ABSTRACT

The existence of a large population of nonequilibrium (hot) phonons after an initial rapid carrier cooling in an undoped multiple GaAs quantum well structure excited by 500fs laser pulses is experimentally verified. An effective carrier depletion time is determined to be as short as 10ps. A mechanism which leads to such a short carrier depletion time is associated with hot phonon enhanced phonon-replica-emission.

KEYWORDS

Nonequilibrium phonon; enhanced phonon-replica-emission; energy relaxation; carrier depletion time; photoexcitation; femtosecond excitation; streak camera; quantum well.

INTRODUCTION

Recently, hot phonon dynamics has been investigated both experimentally (Shah and coworkers, 1985) and theoretically (Lax and coworkers, 1986). In this paper, our experimental results are reported from the measurements of time-resolved photoluminescence (PL) profiles with 2ps time resolution and time-integrated PL spectra from an undoped GaAs MQW structure excited by 500fs laser pulses. The nonequilibrium phonons emitted by hot electrons are directly observed below n=1 electron to heavy-hole transition energy. Its effects on carrier dynamics are (i) to reduce the carrier cooling rate and (ii) to decrease effective carrier depletion time.

SAMPLE and EXPERIMENT

The undoped GaAs/$Al_xGa_{1-x}As$ MQW structure investigated was grown by molecular-beam epitaxy on a (001)-oriented undoped GaAs substrate. The MQW consists of 50 periods of 55Å thick GaAs and 100Å thick $Al_{0.3}Ga_{0.7}As$ layers and followed by a 1.2*um* GaAs buffer layer. An ultrashort light pulse of 500fs duration at 620nm was used to excite the electron-hole pairs with a carrier density of $\sim 10^{19} cm^{-3}$. This light source was generated from a colliding-pulse passive mode-locked dye laser and amplified by a four-stage dye amplifier pumped with a frequency doubled Nd: YAG laser at 20Hz. The PL was spectrally filtered using various narrow band filters, and temporally dispersed by a 2ps time resolution Hamamatsu streak camera system.

RESULTS and DISCUSSION

Time-integrated luminescence spectra the MQW structure excited by the 500fs laser pulses at various lattice temperatures (T_L) are shown in Fig.1. These spectra were taken in conventional Raman $z(y,y)\bar{z}$ configuration, where z is the growth direction. The peak A arises from n=1 electron to heavy-hole transitions and the peak C is from GaAs buffer layer. The most striking feature of the spectral data is the appearance of an emission band B ~30meV below the n=1 electron to n=1 heavy-hole transition. This B emission band is attributed to the hot phonon enhanced phonon-replica. Phonon-assisted recombination in quantum wells was first observed by Holonyak and coworkers (1980) in laser operation. The following reasons further support the assignment to the B band: (i) This B emission band does not appear in the steady-state PL spectra taken at low power excitation about 1W/cm^2 at 4.3K using a 488nm line of an argon-ion laser. Moreover, the relative time-integrated intensity between B and A bands shown in Fig.1 which is detected under amplified 500fs light pulse excitation decreases as the excitation power density decreases. This contradicts what is generally expected for impurity emission.

(ii) The ratio of emission intensity between B and A emission bands increases at lattice temperature increases. To convince the emission band B arises from phonon-assisted process, we calculate the sum of occupation numbers for both equilibrium phonons (lattice temperature T_L) and hot phonons (carrier temperature T_c) by assuming the carrier temperature is same as the effective temperature for the hot phonons after 30ps (see later discussion on the carrier temperature). The calculated result is shown by the solid line in Fig.2. The fitting of the total phonon occupation number to the obtained intensity ratio from the spectra is impressively good. This implies that the intensity of peak B is well correlated with the LO-phonon population.

(iii) We have also measured the polarization of the emission bands A, B, and C by adopting a "right-angle" (Zucker, 1984) integrated luminescence spectra. It was found that the emission band B detected along the y-direction (emitted at the sample edge) was highly polarized in x-direction, while A and C emission bands were depolarized. The intensity ratio between x- and z-direction for B band was about 20 and independent of lattice temperatures from 4.3 to 300K at full excitation power density P_m. The polarization behavior of B band is consistent with the Raman scattering measurements reported by Zucker *et al.;* therefore, supports the B emission band is activated by hot LO phonons.

Time-resolved PL of the MQW structure at 4.3K are shown in Fig.3 for various emitted photon energies. The emission centered at 770nm arise from the recombination of electrons and heavy-holes near the respective first subband-edges. The time-resolved luminescence intensity of the phonon replica is shown in Fig.3 by the emission centered at 780nm which is delayed by ~2ps relative to the 770nm emission.

The experimentally determined values of T_c as function of time is plotted as the solid curve in Fig.4. The shaded area reflects the extent of the uncertainty in deducing the carrier temperature within the first 4ps due to our limited time resolution. The phonons emitted by the hot electrons are reabsorbed by the electrons as a reverse process of the emission giving rise to a slower cooling of the hot-carriers after 5ps.

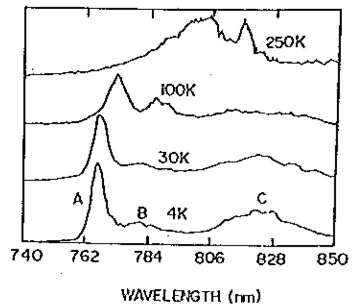

Fig.1 The time-integrated luminescence spectra at various lattice temperatures. The peaks A B and C are explained in the text.

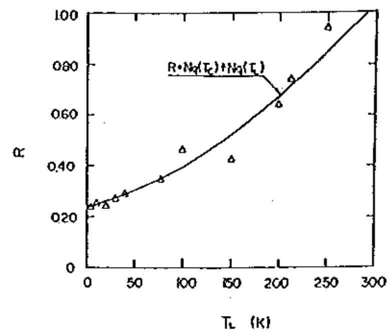

Fig.2 The triangles are the ratios of the peak intensity of B and A indicated in Fig.1. The solid curve is explained in the text.

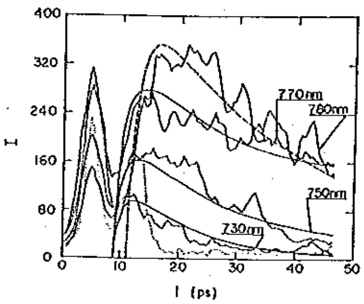

Fig.3 Time-resolved photoluminescence profiles (thin solid curves) from the MQW at 4K at various wavelengths.

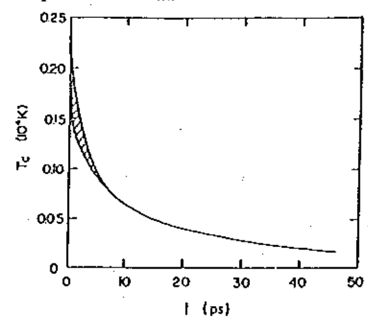

Fig.4 Experimentally determined carrier temperature as function of time. The shaded area indicates the extent of uncertainty in deducing carrier temperature within first 4ps.

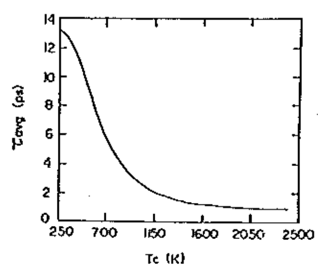

Fig.5 Experimentally determined average phonon emission time as function of carrier temperature.

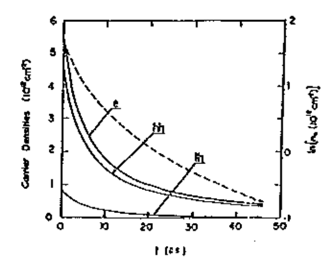

Fig.6 Experimentally determined carrier densities as function of time. e for electron hh for heavy-hole and lh for light-hole. The broken curve is the nature logarithm plot of electron density.

The average phonon emission time (τ_{avg}) (Yang, 1985; Ryan, 1984) for hot carrier to emit a LO phonon as function of the carrier temperature is plotted in Fig.5. As can be seen the τ_{avg} is not a constant but carrier temperature dependent and hence time dependent. The theoretical predicted value should be $\sim 0.16ps$ which is consistent with our value within the limited time resolution. As soon as a large hot phonon population is built up the carrier cooling is suppressed due to re-heating resulting in a larger τ_{avg}.

The initial carrier population can be obtained using experimentally determined distribution function $f_{e,h}$ and is plotted in Fig.6. The salient feature of the data in the Fig.6 is that the carrier density decreases non-exponentially and very rapidly within first 30ps after the end of 0.5ps pulse excitation. One can not define a single carrier lifetime due to the non-exponential of the density curves. However, an effective carrier depletion time [density decreases by a factor of e^{-1} from $n_e(t=0)$] is deduced to be as short as 10ps. Such a short initial carrier depletion time $\sim 10ps$ arises from the participation of hot phonons which enhance phonon-replica-emission centered at $\sim$ 780nm. This phonon-replica-emission is mainly radiated in x-y plane.

CONCLUSION

With 2ps time resolution we are able to study the initial energy relaxation of the hot carriers and the decrease of carrier density simultaneously. The existence of a large population of hot phonons in highly excited semiconductor quantum well structures is experimentally verified. Its effect on the energy relaxation is to slow down the cooling rate after an initial rapid cooling (0-5ps). A new mechanism to explain the ultrashort carrier depletion time $\sim 10ps$ deduced from the fitting of time-resolved PL profiles at various emitted photon energies is proposed to be associated with hot phonon enhanced phonon-replica-emission rather than other nonradiative processes.

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