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Resonant Γ -X-transfer in GaAs/AlAs quantum-well structures

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Abstract. We investigate the Γ_2 - X_{z1} intersubband dynamics in GaAs/AlAs quantum-well structures by time-resolved infrared pump and probe experiments. In the studied structure, the second Γ -level in GaAs is nearly resonant to the first X_z -level in AlAs. We observe a biexponential decay of the bleaching signal with a fast time constant in the order of 1 ps and a second slower time constant of about 7 ps at 10 K and 4 ps at 300 K, respectively. The long term decay represents the X_z - Γ_2 transfer by elastic Γ -X scattering at low temperatures. At 300 K electron-LO-phonon-scattering accelerates the Γ -X transfer.

Introduction

Investigation of intersubband carrier dynamics is very important for application of quantum well structures as infrared devices. In particular, GaAs/AlAs structures are promising candidates for infrared photodetectors (QWIPs) [1] and quantum cascade lasers (QCLs) [2]. As these structures have extreme deep quantum wells (~ 1 eV) the dark current in QWIPs is strongly reduced and the operating temperature in QCLs is increased. However, in GaAs/AlAs quantum well structures intersubband dynamics not only occurs in the Γ -valley of the GaAs layers but also the AlAs barriers, which are the quantum wells for X-electrons, have to be considered. At the heterointerface Γ -X-mixing takes place, that significantly influences the intraband carrier dynamics [3]. Recently, a laser scheme with strong population inversion between mixed Γ and X states in GaAs/AlAs-structures has been proposed in [4].

1. Sample structure and experimental method

The investigated GaAs/AlAs quantum well structure consists of 100 layers with 10 nm wide GaAs quantum wells embedded in between 2.5 nm thick AlAs layers. The central 5 nm of the wells are doped by silicon with a concentration of $6 \times 10^{17} \text{ cm}^{-3}$. The structure is grown by MBE on a semiinsulated GaAs (100) substrate. According to our band structure calculations the first excited Γ -state in GaAs is nearly in resonance with the ground X_z state in AlAs and Γ -X-mixing occurs (see Fig. 1(a)), corresponding to an overlap integral $S_{\Gamma X} = |\langle \psi_{\Gamma 2} | \psi_{X 1} \rangle|^2 = 0.03$.

The relaxation measurements are performed by a Nd:glass laser system of 8 Hz repetition rate with two travelling wave IR dye lasers and two difference frequency mixing stages [5]. The system generates two pulses of 2 ps duration and a spectral width of 10 cm^{-1} independently tunable between 800 cm^{-1} and 2500 cm^{-1} . One of the two infrared pulses excites electrons at a well defined pump frequency $\tilde{\nu}_{\text{pump}}$ from the ground subband to the excited subbands. The subsequent change of the intersubband absorption is measured time-resolved by the second weaker infrared pulse at $\tilde{\nu}_{\text{probe}}$.

2. Results and discussion

The absorption spectra shown in Fig. 1(b) represent the transition between the Γ_1 - and the Γ_2 -state which has a strong Γ -character at small k [see Fig. 1(a)]. At 10 K the peak frequency is located at 915 cm^{-1} . At higher temperatures the typical redshift and broadening of the absorption lines from 50 cm^{-1} at 10 K to 73 cm^{-1} at 300 K are observed. The absorption $\alpha L = -\ln T$ decreases from 2.5 at 10 K to 1.5 at 300 K.

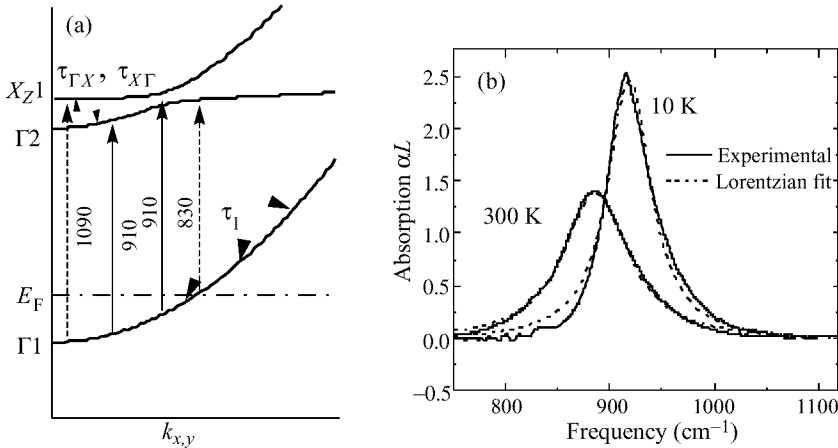


Fig. 1. (a) Schematic conduction band dispersion for the GaAs/AlAs QW structure in the presence of Γ -X-mixing. Arrows indicate the possible transitions at $T = 10 \text{ K}$. (b) Intersubband absorption spectra.

Pump and probe measurements at different pump frequencies with a probe frequency at the Γ_1 - Γ_2 resonance are compared for $T = 10 \text{ K}$ [5] and $T = 300 \text{ K}$. For $T = 10 \text{ K}$ the transmission changes at $\tilde{\nu}_{\text{probe}} = 910 \text{ cm}^{-1}$ are plotted in Fig. 2 after excitation at

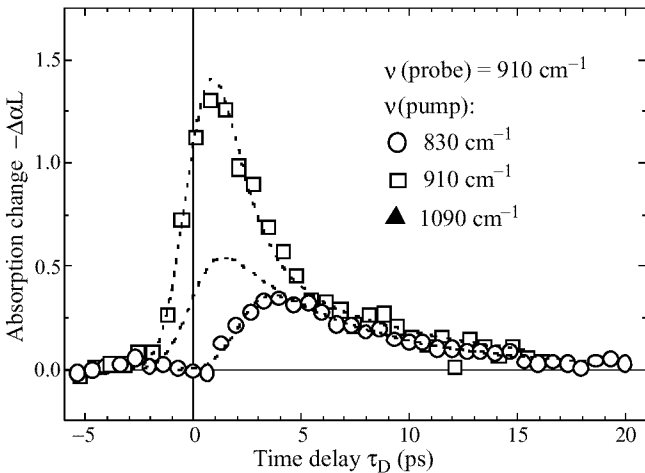


Fig. 2. Time resolved absorption change at $T = 10 \text{ K}$ after excitation at different pump frequencies. Dashed lines are fits of the experimental data by solving rate equations.

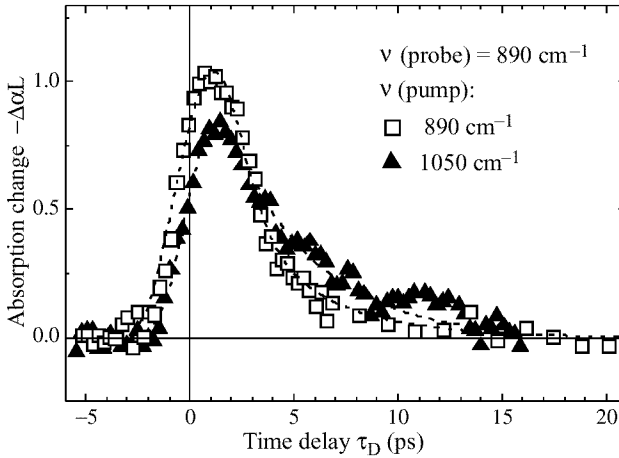


Fig. 3. Time resolved absorption change at $T = 300$ K after excitation at different pump frequencies. Dashed lines are fits of the experimental data by solving rate equations.

$\tilde{\nu}_{\text{pump}} = 830, 910$ and 1090 cm^{-1} . Excitation in the center of the intersubband absorption line at 910 cm^{-1} occupies Γ and X_z states [see Fig. 1(a)] and leads to a biexponential behavior of the relaxation signal with a fast relaxation time $\tau_1 = 1.2$ ps and a long term decay $\tau_2 = 7.0$ ps. In contrast, pumping at 830 and 1090 cm^{-1} excites states with strong X_z character and a decay dominated by the long relaxation time τ_2 is found. This observation can be explained by a rapid $\Gamma_2 \rightarrow \Gamma_1$ recovery time τ_1 together with long term carrier scattering processes between the nearly resonant Γ_2 - and X_{z1} -valleys, which are strongly coupled [3]. For $T = 300$ K the transmission changes at $\tilde{\nu}_{\text{probe}} = 890 \text{ cm}^{-1}$ are shown in Fig. 3 after excitation at $\tilde{\nu}_{\text{pump}} = 890$ and 1050 cm^{-1} . Similar to the measurements at low temperature two relaxation times are observed. Pumping in the center of the absorption band we obtain two time constants, 1 ps for the fast decay and about 4 ps for the long term decay. The curve for the pump frequency of 1050 cm^{-1} only shows the long relaxation time.

For a detailed interpretation of the results the energy dispersion diagram of the studied structure is considered [Fig. 1(a)]. Under excitation, the electrons fill the Γ - X -mixed subbands. Due to the Γ - X interaction at the heterointerface direct transitions to the X_{z1} -subbands become possible. Absorption of light due to Γ_1 - X_z transitions was already detected in GaAs/AlAs quantum-well structures previously [1]. Thus for intense excitation in and around the absorption peak, both Γ_1 - Γ_2 and Γ_1 - X_{z1} optical transitions take place. As the energy dispersions for Γ and X electrons are strongly different, the absorption band for intervalley transitions must be broader than that for Γ - Γ transitions. Consequently, in spite of the weak oscillator strength of the Γ_1 - X_{z1} transition, it dominates the absorption change at pump frequencies at the feet of the absorption line, where the absorption coefficient for the Γ_1 - Γ_2 transition is negligibly small. On the other hand, intervalley scattering processes play a key role in carrier relaxation. After excitation, electrons are redistributed among the second Γ -subband and the X_z -subband and vice versa. Electron-LO-phonon scattering and elastic electron scattering due to the interface mixing potential (Γ - X_z mixing) are relevant mechanisms for the Γ - X transfer in GaAs/AlAs type II superlattices [3, 7]. In our sample electron-LO-phonon scattering is believed to be of minor importance at low temperature, because the separation of the coupled Γ_2 - and X_{z1} -subbands (about 15 meV)

is below the optical phonon energy. Therefore, the elastic electron scattering due to the interface mixing potential is expected to dominate the transfer process between the Γ_2 and X_{z1} -states of the AlAs barrier at 10 K [2]. At 300 K also electron-LO-phonon-scattering becomes possible due to the increased phonon occupation probability and a shorter time constant τ_2 is observed.

Electrons return from AlAs to GaAs mainly via the Γ_2 -subband, as transitions into the Γ_1 -subband are suppressed because of the smaller overlap integral. The X_1 - Γ_2 relaxation time $\tau_{X\Gamma}$ can be determined for pump frequencies at the feet of the absorption line, when electrons are directly excited into subband states with strong X_{z1} character. Due to the lower density of states in the Γ -valley compared to the X-valley X - Γ scattering times $\tau_{X\Gamma}$ are longer than Γ - X scattering times $\tau_{\Gamma X}$.

Modell calculations using rate equations show the best fit with $\tau_1 = 0.8$ ps, $\tau_{\Gamma X} = 2.5$ ps and $\tau_{X\Gamma} = 4.5$ ps for $T = 10$ K and $\tau_1 = 0.6$ ps, $\tau_{\Gamma X} = 2.0$ ps, $\tau_{X\Gamma} = 2.5$ ps for $T = 300$ K, respectively [3].

3. Conclusion

We have directly observed the influence of Γ - X mixing on intersubband relaxation in a GaAs/AlAs quantum-well structure. The resonant intersubband carrier transfer from the Γ valley in GaAs to the X_z valley in AlAs and vice versa, has been observed at 10 K. At room temperature an additional electron-LO-phonon-scattering channel enhances the transfer rates.

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