Resonant gamma-X-Transfer in GaAs/AlAs Quantum-Well Structures

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:
TITLE: Nanostructures: Physics and Technology International Symposium [9th], St. Petersburg, Russia, June 18-22, 2001 Proceedings
To order the complete compilation report, use: ADA408025

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP013147 thru ADP013308

UNCLASSIFIED
Resonant $\Gamma$–X-transfer in GaAs/AlAs quantum-well structures

S. R. Schmidt†, A. Seilmeyer†, E. A. Zibik‡, L. E. Vorobjev‡, A. E. Zhukov§ and V. M. Ustinov§
† Institute of Physics, University of Bayreuth, D-95440 Bayreuth, Germany
‡ St. Petersburg State Technical University, St Petersburg 195251, Russia
§ Ioffe Physico-Technical Institute, St Petersburg, Russia

Abstract. We investigate the $\Gamma_2$–$X_{z1}$ intersubband dynamics in GaAs/AlAs quantum-well structures by time-resolved infrared pump and probe experiments. In the studied structure, the second $\Gamma$-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 $X_z$–$\Gamma_2$ transfer by elastic $\Gamma$–X scattering at low temperatures. At 300 K electron-LO-phonon-scattering accelerates the $\Gamma$–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 ($\sim 1$ 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 $\Gamma$-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 $\Gamma$–X-mixing takes place, that significantly influences the intraband carrier dynamics [3]. Recently, a laser scheme with strong population inversion between mixed $\Gamma$ 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 $6 \times 10^{17}$ cm$^{-3}$. The structure is grown by MBE on a semiinsulated GaAs (100) substrate. According to our band structure calculations the first excited $\Gamma$-state in GaAs is nearly in resonance with the ground $X_z$ state in AlAs and $\Gamma$–X-mixing occurs (see Fig. 1(a)), corresponding to an overlap integral $S_{\Gamma X} = | \langle \psi_{\Gamma 2} | \psi_{X1} \rangle |^2 = 0.03$.

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 [4]. 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 $\tilde{v}_{\text{pump}}$ 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 $\tilde{v}_{\text{probe}}$. 

254
2. Results and discussion

The absorption spectra shown in Fig. 1(b) represent the transition between the \( \Gamma_1 \)- and the \( \Gamma_2 \)-state which has a strong \( \Gamma \)-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.

Pump and probe measurements at different pump frequencies with a probe frequency at the \( \Gamma_1-\Gamma_2 \) resonance are compared for \( T = 10 \) K [ ] and \( T = 300 \) K. For \( T = 10 \) K the transmission changes at \( \nu_{\text{probe}} = 910 \) cm\(^{-1}\) are plotted in Fig. 2 after excitation at

![Fig. 1. (a) Schematic conduction band dispersion for the GaAs/AlAs QW structure in the presence of \( \Gamma-X \)-mixing. Arrows indicate the possible transitions at \( T = 10 \) K. (b) Intersubband absorption spectra.](image)

![Fig. 2. Time resolved absorption change at \( T = 10 \) K after excitation at different pump frequencies. Dashed lines are fits of the experimental data by solving rate equations.](image)
$v_{\text{pump}} = 830, 910$ and $1090$ cm$^{-1}$. Excitation in the center of the intersubband absorption line at $910$ cm$^{-1}$ occupies $\Gamma$ 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 $\tau_2$ is found. This observation can be explained by a rapid $\Gamma_2 \rightarrow \Gamma_1$ recovery time $\tau_1$ together with long term carrier scattering processes between the nearly resonant $\Gamma_2$- and $X_{z1}$-valleys, which are strongly coupled [8].

For $T = 300$ K the transmission changes at $v_{\text{probe}} = 890$ cm$^{-1}$ are shown in Fig. 3 after excitation at $v_{\text{pump}} = 890$ 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 $\Gamma$–$X$-mixed subbands. Due to the $\Gamma$–$X$ interaction at the heterointerface direct transitions to the $X_{z1}$-subbands become possible. Absorption of light due to $\Gamma_1$–$X_{z}$ transitions was already detected in GaAs/AlAs quantum-well structures previously [9]. Thus for intense excitation in and around the absorption peak, both $\Gamma_1$–$\Gamma_2$ and $\Gamma_1$–$X_{z1}$ optical transitions take place. As the energy dispersions for $\Gamma$ and $X$ electrons are strongly different, the absorption band for intervalley transitions must be broader than that for $\Gamma$–$\Gamma$ transitions. Consequently, in spite of the weak oscillator strength of the $\Gamma_1$–$X_{z1}$ transition, it dominates the absorption change at pump frequencies at the feet of the absorption line, where the absorption coefficient for the $\Gamma_1$–$\Gamma_2$ 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 $\Gamma$-subband and the $X_{z1}$-subband and vice versa. Electron-LO-phonon scattering and elastic electron scattering due to the interface mixing potential ($\Gamma$–$X_z$ mixing) are relevant mechanisms for the $\Gamma$–$X$ transfer in GaAs/AlAs type II superlattices [4, 7]. In our sample electron-LO-phonon scattering is believed to be of minor importance at low temperature, because the separation of the coupled $\Gamma_2$- 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 $\Gamma_2$ and $X_{\pm 1}$-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 $\tau_2$ is observed.

Electrons return from AlAs to GaAs mainly via the $\Gamma_2$-subband, as transitions into the $\Gamma_1$-subband are suppressed because of the smaller overlap integral. The $X_1-\Gamma_2$ 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 $X_{\pm 1}$ character. Due to the lower density of states in the $\Gamma$-valley compared to the $X$-valley $X-\Gamma$ scattering times $\tau_{X\Gamma}$ are longer than $\Gamma-X$ 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 [4].

3. Conclusion

We have directly observed the influence of $\Gamma-X$ mixing on intersubband relaxation in a GaAs/AlAs quantum-well structure. The resonant intersubband carrier transfer from the $\Gamma$ valley in GaAs to the $X_2$ 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.

References