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Saturation of Intersubband Transitions in P-doped GaAs/AlGaAs Quantum Wells.

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Optical saturation experiments have been performed on hh1-hh2 intersubband transitions in two samples of p-doped GaAs/AlGaAs quantum wells. The transitions had energies of 183meV and 160meV and the measured population relaxation times were 2 ± 1.5 ps and 0.3 ± 0.1 ps respectively. Modelling of the quantum wells with a 6×6 k-p method shows that intersubband scattering by LO phonons can account for these relaxation times. The valence bandstructure is typically more complicated than the conduction bandstructure in a quantum well but these measurements show that LO phonons are the dominant intersubband scattering mechanism in both cases.

Intersubband transitions (ISBTs) in the valence band of GaAs/AlGaAs Quantum Wells (QW) have received less attention than those of the conduction band [1]. In the valence band case mixing, between the heavy hole and light hole bands, leads to subbands that are strongly non-parabolic [1]. This band mixing also modifies the absorption selection rules; valence band ISBT's offer the possibility of absorbing normally incident radiation, [1] although the hh1-hh2 transitions studied here absorbed only light polarised along the growth direction in the same way as conduction band ISBTs.

first consisted of 50 QWs, each consisting of a 3.1nm wide GaAs layer, that were separated by 30nm wide $\text{Al}_{0.57}\text{Ga}_{0.43}\text{As}$ barriers. For growth reasons the barriers were grown as a digital alloy stack of AlAs & GaAs with respective thicknesses of 1.13nm and 0.85nm. The second sample had 25, 3.7nm wide, GaAs QWs, separated by similar barriers to the first. Both samples were modulation doped, to a nominal sheet hole density of $p_{\text{qw}}=1.6 \times 10^{12} \text{ cm}^{-2}$ by adding a layer doped with $1.6 \times 10^{18} \text{ cm}^{-3}$ carbon atoms in the centre of the barriers.

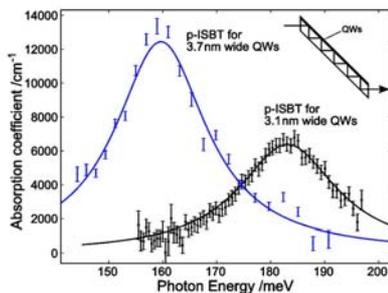


Figure 1: (colour online) Spectra from the two p-doped samples showing their p-ISBTs at 17K, which have been fitted with Lorentzian lineshapes. The transition peaks occurred at 160(1) meV and 183(1)meV respectively. The dipole matrix elements were calculated as 0.82nm for the 3.7nm wide QWs and 0.6nm for the 3.1nm wide QWs. The inset shows a side view of the path that the light took through the sample rhomb geometry.

The two multiple QW samples studied here were previously reported in ref. [2]. Both were grown on 500 μm thick (100) semi-insulating GaAs wafers. The

Figure 1 shows the absorption spectra of the two samples taken, at 17 K, with a laser intensity low enough to give spectra identical to those acquired by a Fourier Spectrometer (Fig.2). The samples were polished into rhombs with the light focused into them with a 50mm focal length lens, making 10 internal reflections and passing through the QWs at 45° (see inset of Fig. 1), so as to optically couple to the z-polarised hh1-hh2 transition [2]. At T=17K, the absorption linewidths were 22.0(5)meV for the 3.1nm wide MQW sample and 20.5(5)meV wide for the 3.7nm wide MQW sample, but both samples' small signal absorption spectra show rapid broadening [2] as the carrier temperature increases (see fig. 2). This is a signature of the strongly non-parabolic nature of the valence bands, leading to prominent valence-band ISBT inhomogeneous broadening as the holes are thermally promoted to states with increasing in-plane wave-vector.

The saturation experiments measured the absorption of a sample for various quantified incident intensities. The intensity was varied over 2-3 orders of magnitude, by moving attenuators from one side of the sample to the other, in this way the intensity at the detector was left almost unchanged. Because light polarised within the plane of the QW did not couple to the transition of interest, the s-polarised transmitted signal could be used for normalising the p-polarised transmission spectra to extract exact ISBT absorptance values.

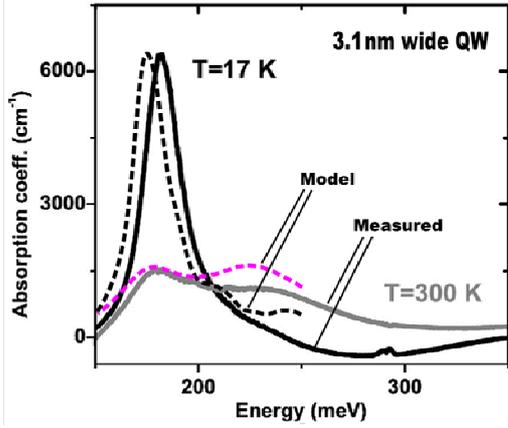


Figure 2: (colour online) The large temperature variance (compared with n-ISBTs) of the p-ISBT's lineshape for the 3.1 nm wide QW sample. The experimental FTIR spectra are replicated from [2] and overlaid are theoretical absorption spectra from the 6×6 k-p model described in the text.

The experiments used an optical parametric generator comprising a ZnGeP_2 crystal [3] as a mid-infrared light source, tunable between $\lambda = 6.4\text{-}8.6\mu\text{m}$ (idler beam). The crystal was pumped with $\lambda = 2.8\mu\text{m}$ wavelength, modelocked laser pulses and produced 100 ps long pulses of $\sim 3\mu\text{J}$ energy. Gaussian Beam cross sections along the light path were measured using a series of knife edge tests and the pulse energy measured using a calibrated large area pyrodetector. The infrared light was focussed to $100\mu\text{m}$ diameter beam spot onto the rhomb facet, generating peak intensities of up to 200MWcm^{-2} . Figure 3 shows the saturation curves for both samples i.e. the change in ISBT absorption with changing intensity incident on the sample.

At low intensities, when the carrier excitation rate is much less than the net population relaxation rate, the ISBT absorption spectra are intensity independent. At high intensities, the absorption saturates due the rate of photon absorption (and stimulated emission) being larger than the population relaxation rate; quantifying this saturation enables the population relaxation rate to be measured. At $T=17\text{K}$, the ISBTs were taken to be homogeneously broadened, as evidenced by their narrow Lorentzian lineshapes, and in such cases a rate equation model for a two level system yields [4]

$$\alpha = \frac{\alpha_0}{1 + I/I_{sat}} \quad (1)$$

where α_0 is the small signal absorption coefficient and I_{sat} , the saturation intensity, is given by

$$I_{sat} = \frac{p_{qw}\hbar\omega_{12}}{2\alpha_{12}\tau_{21}} \quad (2)$$

here p_{qw} is the areal hole density in the QW, ω_{12} is the transition energy, α_{12} is the fractional absorption per quantum well and τ_{21} is the population relaxation time for holes from $\text{hh}2$ to $\text{hh}1$. To analyse the experimental data, this expression has to be modified to allow for the way the intensity decreases as the light propagates through an optically thick sample [4] and for the effects of the oblique angle of incidence, θ , leading to

$$\ln\left(\frac{I_f}{I_0}\right) + \frac{\sin^2\theta}{\cos\theta} \frac{I_f - I_0}{I_{sat}} = -\alpha_{12}M \frac{\sin^2\theta}{\cos\theta} \quad (3)$$

where M is the number of quantum wells in the sample and I_0 and I_f are the initial and final intensities. To account for the way the Gaussian beam profile propagates through the sample, a numerical integration of the above equation was performed; this included the standing wave effects caused by the total internal reflection in the rhomb sample geometry that double the effective intensity experienced by the sample's ISBTs [5, 6].

In the case of electron ISBTs it is accepted that, provided the ISBT energy exceeds that of the LO phonon, intersubband scattering is dominated by the emission of LO phonons [1]. To investigate whether LO phonons are the dominant mechanism for valence subbands, the samples' relaxation times were modelled using a bandstructure calculated with a 6×6 k-p method [1] that accounted for full anisotropy and nonparabolicity of valence subbands and for the in-plane wave vector dependence of the transition matrix elements. Hartree self-consistent effects were taken into account, as well as the depolarization shift for z-polarized optical intersubband transitions. Finally a degree of interdiffusion between the layers of the digital alloy had to be included to get the best fit to the measured small-signal absorption curves.

This bandstructure was then used to calculate the expected relaxation times due to LO phonon scattering, with both polar and deformation potential interactions accounted for [7,8]. Both samples had $\text{lh}1$ subbands lying $\sim 50\text{meV}$ below their $\text{hh}1$ subbands e.g. between $\text{hh}1$ and $\text{hh}2$, so the relaxation from $\text{hh}2$ could go either directly ($\text{hh}2 \rightarrow \text{hh}1$) or indirectly ($\text{hh}2 \rightarrow \text{lh}1 \rightarrow \text{hh}1$). The k.p calculations show that the $\text{lh}1 \rightarrow \text{hh}1$ relaxation rate is faster than the other two by almost an order of magnitude, and that the two paths have approximately

equal shares in the total relaxation rate. The high speed of the $lh1 \rightarrow hh1$ process prevented the $lh1$ state from becoming a bottleneck for relaxation so, in terms of their relaxation dynamics, these samples behaved as simple two-level systems [justifying the use of equations (1) and (2)], albeit with a relaxation rate that was the sum of two parallel relaxation channels.

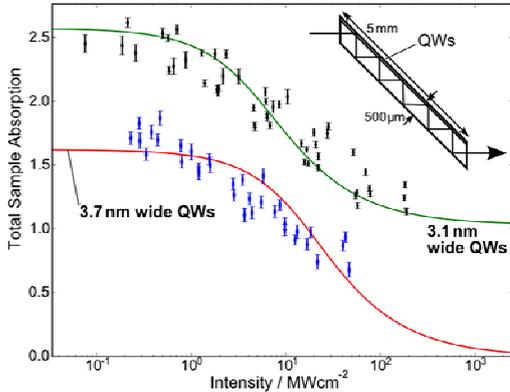


Figure 3: (colour online) Absorption saturation of the two samples' p-ISBTs. The y-axis shows the overall sample absorption (defined as $\alpha = -\ln(T)$, where T is the transmission of the ISBT's) and the curve for the 3.1 nm QW has been vertically shifted by +1 unit for clarity. For the 3.7nm wide QWs, the incident light was tuned to the ISBT peak at 160meV photon energy and the shown theoretical fit yielded I_{sat} as $9=3MWcm^{-2}$ resulting in a population relaxation time of $\tau_{21} = 0.3 \pm 0.1ps$. Likewise, the 3.1nm wide QW had a peak energy of 183meV, a saturation intensity of $3=2MWcm^{-2}$ and $\tau_{21} = 2 \pm 1.5ps$. Inset shows sample absorption geometry.

To explore the influence of carrier heating [9], relaxation times were calculated for effective hole temperatures between 17-150 K, but the best agreement came with the holes in thermal equilibrium with the $T=17K$ lattice. An exact treatment of dynamic phonon screening was not possible, instead we computed relaxation times in the static screening approximation (known to over estimate the relaxation time) and in the complete absence of screening, and present the modeled values as falling somewhere between these two limits.

For the 3.1nm QW's p-ISBT, the model calculated relaxation times in the range 0.73-1.36ps; which is within error of the experimentally measured value of $2 \pm 1.5ps$. Likewise, the 3.7nm QW's p-ISBTs had a predicted a relaxation time of 0.31-0.59ps, comparable to the measured value of $0.3 \pm 0.1ps$. The errors on the measured relaxation times were primarily determined by the way the experimental uncertainty in the laser intensity, at the sample position in the cryostat, propagated through the modeling process.

As far as we are aware, previous studies of relaxation kinetics in p-doped GaAs/AlGaAs QWs have investigated only low-energy $hh1-lh1$ ISBTs. Bezzant et al. [10] measured long relaxation times of 20ps and 55ps for two different samples using pump-probe experiments, but these were in samples whose ISBT

energies ($\sim 20meV$) were too small to allow for the efficient emission of LO phonons ($\hbar\omega_{LO} \sim 36 meV$). Similarly, long lifetimes were seen in p-doped Si/SiGe QWs [9], where the small transition energies and non-polar material gave very weak LO phonon emission, although short ($\sim 250fsec$) times have also been reported in highly excited Si/SiGe samples where multiple inter- and intra- subband relaxation channels, combined with strongly heated carrier distributions to give very fast LO phonon deformation potential scattering¹¹. The dramatic difference between the lifetimes measured here and in previous reports is consistent with LO phonon relaxation making the dominant contribution to the relaxation processes in these large ISBT energy samples.

As discussed in [12], the strength of LO phonon emission in conduction band ISBTs is expected to be proportional to the transition's dipole matrix element, μ_{12} , squared. This is in qualitative agreement with the data; using the modeled dipole values (fig. 1) suggests that this accounts for a factor of ~ 1.9 of the difference between the relaxation times of two samples. The remainder is likely due to the differences in the LO phonon wave-vectors that are coupled to the transitions in the different samples, due to their different in-plane hole dispersion curves.

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- ¹ M. Helm, Chapter 1, 'Intersubband Transitions in Quantum Wells: Physics and Device Applications I', (editors H.C.Liu & F. Capasso), **Semiconductors and Semimetals**, vol.62, academic press (2000)
- ² O. Malis, L. N. Pfeiffer, K.W. West, A.M. Sergent & C. Gmachl, , **Appl. Phys. Lett.** 87, 091116 (2005)
- ³ K.L. Vodopyanov, , **J. Opt. Soc. Am. B** 16 (9) p1579-1586 (1999)
- ⁴ R. Loudon, 'The Quantum Theory of Light', Oxford Uni. Press, 3edn. (2000)
- ⁵ M. Zaluzny & C. Nalewajko, **Phys. Rev. B** 68 (233305) (2003)
- ⁶ M. Zaluzny & C. Nalewajko, **Phys. Rev. B** 59 (20) (1999)
- ⁷ J. M. Hinckley, and J. Singh, **J. Appl. Phys.** 76, 4192 (1994)
- ⁸ R. Scholz, **J. Appl. Phys.** 77, 3219 (1995).
- ⁹ R. W. Kelsall, Z. Ikonc, P. Murzyn, C. R. Pidgeon, P. J. Phillips, P. Harrison, S. A. Lynch, P. Townsend, D. J. Paul, S. L. Liew, D. J. Norris, and A. G. Cullis, **Phys. Rev. B** 71, 115326 (2005)
- ¹⁰ C.D. Bezzant, J.M. Chamberlain, H.P.M. Pellemans, B.N. Murdin, W. Batty, & M. Henini, **Semicond. Sci. and Tech.** 14 (8) L25-L28 (1999)
- ¹¹ R A Kaindl et al. **Phys.Rev. Letts.**86, (6), 1122 (2001).
- ¹² J.F. Dynes, M.D. Frogley, M. Beck, J. Faist, C.C. Phillips, **Phys. Rev. Letts.** 94 (15) p4 (2005)