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Saturation spectroscopy of electronic states in a magnetic field in InAs/$Al_xGa_{1-x}Sb$ single quantum wells

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Abstract

We have carried out saturation spectroscopy of cyclotron resonance in a semiconducting InAs/$Al_{0.5}Ga_{0.5}Sb$ single quantum well using the UCSB free electron laser and have extracted an effective Landau level lifetime using an *n*-level rate equation model. The effective lifetime shows strong oscillations (> an order of magnitude) with frequency. Minima are shifted to higher frequencies than those given by the simple parabolic magnetophonon resonance condition due to large nonparabolicity in the InAs conduction band. We have also used this technique to investigate the origins of two lines: the X-line and cyclotron resonance in a "semimetallic" InAs/$Al_{0.1}Ga_{0.9}Sb$ single quantum-well structure. Results show that the two lines are of different origin. © 1998 Elsevier Science B.V. All rights reserved.

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Saturation spectroscopy has been used in the last few years to determine Landau level (LL) lifetimes in various semiconductor systems [1,2,8]. Such investigations provide important information about fundamental energy loss mechanisms of carriers in high magnetic fields. The effective LL lifetime was found to depend inversely on the electron concentration in a GaAs/AlGaAs single heterostructure [3]. Recently, Vaughan et al. [2] have observed an oscillatory behavior of LL lifetime as a function of frequency (between 11 and 40 meV) in a semimetallic InAs/GaSb double heterojunction (40 nm InAs well). Minima occur approximately at the magnetophonon resonance (MPR) condition, $N\hbar\omega_c = \hbar\omega_{LO}$, $N = 1, 2 \ldots$, and $\hbar\omega_{photon} = \hbar\omega_c$. Here $\hbar\omega_c$ is the cyclotron resonance (CR) energy in the vicinity of the Fermi energy and $\hbar\omega_{LO}$ is the LO-phonon energy (242 cm^{-1}) in InAs. Analysis is complicated in this case by the fact that the sample is semimetallic (the valence band in GaSb is higher in energy than the conduction band in InAs) and has low mobility. In addition, the duration of the laser

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pulses (8–15 ps) is almost comparable to the effective lifetime, so that non-steady-state analysis must be used.

In the present study, to understand the energy relaxation mechanisms between electron Landau levels uncomplicated by the presence of holes, we have investigated the effective LL lifetime (extracted from an n-level rate equation model) at frequencies between 5 and 17 meV, in a high mobility semiconducting InAs/$Al_{0.5}Ga_{0.5}Sb$ (15 nm InAs well) single quantum well. We have observed oscillations in an effective LL lifetime with values similar to those obtained by Vaughan et al. [2]; however, in this instance the minima are shifted to higher frequencies than given by the simple parabolic MPR condition for $N = 2$ and 3. We attribute these shifts to the large nonparabolicity in the InAs conduction band as discussed below. We have also carried out saturation measurements on a “semimetallic” InAs/$Al_{0.1}Ga_{0.9}Sb$ (15 nm InAs well) single quantum-well structure at 124 cm^{-1} to investigate the physical origins of two previously observed lines, i.e., the so-called X-line, which has been attributed to an internal transition of stable excitons [4], and electron CR.

Two samples, both with a single InAs (15 nm) quantum well, but having different $Al_xGa_{1-x}Sb$ barrier compositions ($x = 0.5$ and 0.1), were studied. Sample 1 ($x = 0.5$) is semiconducting with an electron density and mobility of 6.1×10^{11} cm^{-2} and 2.2×10^5 cm^2/Vs, respectively. Sample 2 ($x =$ 0.1) is “semimetallic” ($Al_{0.1}Ga_{0.9}Sb$ valence band overlaps the InAs conduction band by about 50 meV in the absence of confinement) with an electron density of 5.5×10^{11} cm^{-2} and mobility of 0.5×10^5 cm^2/Vs. The saturation spectroscopy experiments were carried out with the UCSB FEL in conjunction with a 12 T superconducting magnet with the sample mounted on a cold finger at ~1.5 K. The UCSB FEL provides peak intensities up to 40 kW/cm^2 (when focused) over the wavelength range between 70 and 800 μm with a variable pulse width between 0.5 and 5 μs at a repetition rate of approximately 1Hz. Measurements were made under steady-state conditions as all the relevant lifetimes are much shorter (order of nsec or less) than the 3.2 μs FEL pulse width used in these experiments. A small split-off reference signal was detected by a pyroelectric detector, and a 4.2 K germanium bolometer was used to detect the signal transmitted through the sample. A digital oscilloscope was used to average (over four FEL pulses) the ratio of the transmitted signal to the reference signal. Far infrared radiation was focused on the sample with mirror optics. Photon energies between 51 and 130 cm^{-1} were used in this study.

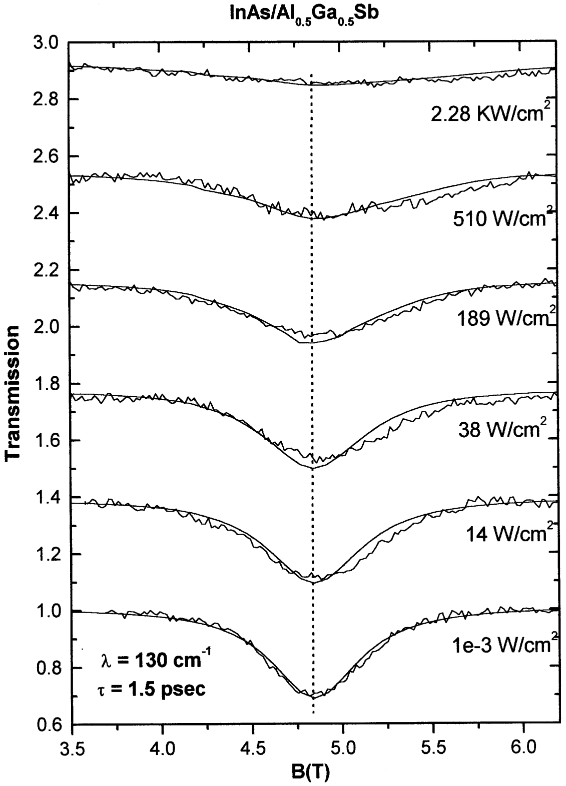

Fig. 1. The CR transmission spectra at 130 cm^{-1} at several intensities for sample 1. Solid smooth lines are the results of simulation using an n-level rate equation model for $\tau = 1.5$ ps.

A typical series of magneto-transmission spectra is shown in Fig. 1 for several laser intensities at 130 cm^{-1}. At low laser intensities, the cyclotron resonance absorption lines are quite strong (33% for the linearly polarized FEL beam). As the FEL intensity (corrected for reflection) increases, the absorption clearly decreases, and the linewidth broadens while shifting to higher magnetic fields. At the highest intensity, the CR is almost

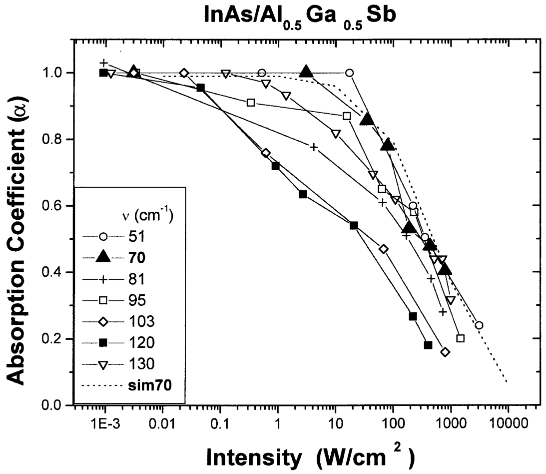

Fig. 2. Absorption coefficient versus intensities at different laser frequencies. Dotted line is a fit described in the text. Solid lines are guides to the eye.

completely saturated. Nearly complete saturation of CR was obtained at all the FEL frequencies used.

The peak intensity absorption coefficient (α) is plotted as a function of intensity for several FEL frequencies in Fig. 2. The peak intensity absorption coefficient is obtained from $\alpha = -\ln((2I/I_0) - 1)$, where I_0 is the background intensity transmitted far from resonance, and I is the intensity transmitted at CR (transmission minimum), taking into account the fact that only half of the linearly polarized FEL beam satisfies the circular polarization selection rule for CR absorption. Several features can be noted from this plot. For the 120 and 103 cm^{-1} laser lines α decreases to half its low intensity value at approximately one order of magnitude lower intensity than for the other laser lines. Also, these two lines begin to saturate at very low intensity, while complete saturation occurs above 1 $\mathrm{kW/cm}^2$. The low-frequency lines (50 and 71 cm^{-1}) do not show evidence of saturation until high intensities are reached, and then saturate rapidly. The 130 and 95 cm^{-1} lines show signs of saturation at intermediate intensities, and reach complete saturation only at very high intensities.

To extract an effective Landau level lifetime from CR saturation data, we have developed an n-level rate equation model taking into account non-parabolicity [5] in the InAs conduction band. We find that ten Landau levels or more are significantly populated at higher powers. For simplicity, we have taken the same lifetime for all Landau levels, $\tau_n = \tau$, and have considered non-radiative transitions only between adjacent Landau levels. For each Landau level n, a rate equation accounting for stimulated absorption, stimulated emission and non-radiative emission can be written as

$$\begin{aligned} \mathrm{d}N_n/\mathrm{d}t = {} & \sigma_{n-1} I N_{n-1} f_n - \Gamma_{n-1} N_n f_{n-1} \\ & - \sigma_{n-1} I N_n f_{n-1} - \sigma_n I N_n f_{n+1} \\ & + \Gamma_n N_{n+1} f_n + \sigma_n I N_{n+1} f_n, \end{aligned}$$

where I is the flux of incident photons, N_n is the carrier density of the nth LL, $\Gamma = 1/\tau$ is the spontaneous transition rate, $f_n = 1 - N_n/g$ is the fractional number of available states of the nth LL (g is the LL degeneracy), and σ_n is the absorption cross section for the nth LL. These coupled rate equations are solved numerically under steady-state conditions with τ as an adjustable parameter. An example of the results of this simulation is shown in Fig. 2 (dotted line) at 70 cm^{-1} with $\tau = 0.5$ ps; the fit is very good. Lifetimes are extracted for all the laser frequencies with this procedure. The lifetime thus obtained for a particular laser frequency is used to simulate the transmission spectra from the above model. These results are shown by the smooth solid lines in Fig. 1 for 130 cm^{-1}. The simulation reproduces reasonably well the general features of the transmission data (the line broadens and shifts to higher fields with increasing power), but underestimates the absorption for higher intensities at higher fields. This discrepancy may be due to the fact that at high laser intensities higher Landau levels are significantly populated. The MPR condition ($N = 2$) between a pair of these higher Landau levels is satisfied more precisely at higher fields, since the spacing between Landau levels becomes smaller with increasing energy. This can result in a significant depopulation of a higher Landau level (at the MPR condition), leading to increased absorption from the adjacent (lower) Landau level. This is not taken into account by the model.

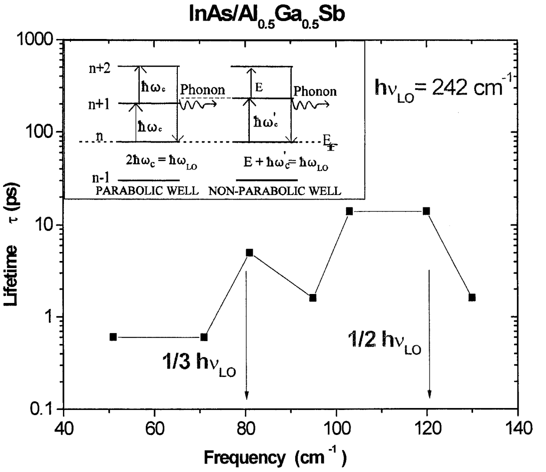

Fig. 3. The effective Landau-level lifetime from an n-level rate equation model is plotted as a function of frequency. MPR conditions are shifted to higher frequencies ($\hbar\omega'_c > \hbar\omega_c$) for a nonparabolic well as shown in the inset.

The effective lifetimes obtained from the model show strong oscillations with frequency (> one order of magnitude) as shown in Fig. 3. When the MPR condition is satisfied, one expects large resonant enhancement of the scattering rate (minima in lifetime) due to LO-phonon emission from Landau levels that lie $\hbar\omega_{LO}$ above partially occupied Landau levels. Since the LO-phonon energy for InAs is 242 cm^{-1}, the MPR conditions for a simple parabolic InAs conduction band (equally spaced Landau levels) are satisfied at 121 cm^{-1} ($N = 2$) and 81 cm^{-1} ($N = 3$). In contrast, the present results show minima around 90–95 and 130 cm^{-1} and maxima around 80 and 110 cm^{-1}. Due to nonparabolicity, the energy spacings between adjacent Landau levels become smaller with increasing energy as shown in the inset of Fig. 3. Hence, the MPR condition for $N = 2$ will be satisfied when $E + \hbar\omega'_c = \hbar\omega_{LO}$, rather than $2\hbar\omega_c = \hbar\omega_{LO}$ which is the case for parabolic dispersion. Since $E < \hbar\omega_c$ due to nonparabolicity, $\hbar\omega'_c$ must be greater than $\hbar\omega_c$ for the MPR condition to be satisfied. Hence, the MPR conditions are satisfied at higher photon frequencies. A simple calculation of the nonparabolicity predicts the MPR conditions to be satisfied around 127 cm^{-1} ($N = 2$) and 90 cm^{-1} ($N = 3$), in reasonable agreement with the experimental results. Also, at high laser intensities, higher (lower) Landau levels become significantly populated (depopulated), and LO-phonon emission between these Landau levels becomes possible whenever MPR conditions are satisfied. This not only shifts the resonance conditions to higher frequencies, but also makes it harder to saturate CR at higher laser intensities. This is observed for all the laser frequencies: most clearly for 103 and 119 cm^{-1} lines as shown in Fig. 2.

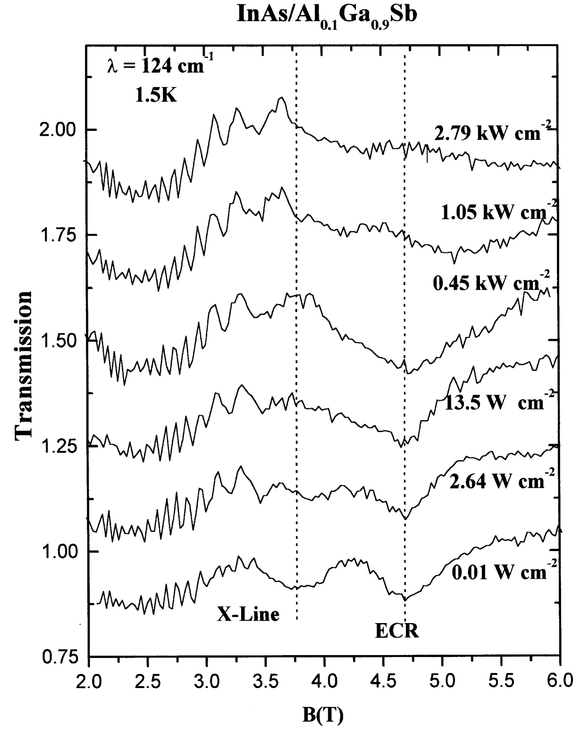

Fig. 4. Transmission spectra at 124 cm^{-1} at several laser intensities for sample 2.

We have also carried out saturation measurements on the “semimetallic” InAs/Al$_{0.1}$Ga$_{0.9}$Sb single quantum well at 124 cm^{-1} in order to investigate the origins of two absorption lines previously reported [4]. Results are shown in Fig. 4. The lower frequency line (the X-line) has been attributed to an internal transition of spatially separated excitons [4] and the other line to electron CR. Recently, Chiang et al. [6] have attributed these two lines to spin-split cyclotron resonance lines, the large separation arising from the unique band structure [7]. In the present experiment, the X-line saturates at a much lower laser intensity (more than two orders of magnitude) than CR, clearly indicating their different physical origin. This is consistent with the assignment of this line to an internal transition of a stable exciton. Conversely, the CR line initially gains strength and then starts to saturate with further increase in laser intensity. The initial increase in CR strength is also consistent with the fact that excitons can be impact ionized at high laser intensities, creating free electrons and holes. Another interesting feature in Fig. 4 is the presence of oscillations during transmission at low magnetic fields. These oscillations seem to be periodic in 1/B, but the period does not correspond to the electron density. The origin of the oscillations is not known.

In conclusion, we have observed strong oscillations (>an order of magnitude) in the effective Landau level lifetime with frequency in a semiconducting InAs/$Al_{0.5}Ga_{0.5}Sb$ sample, with minima at the modified MPR conditions for the nonparabolic InAs conduction band. For the semimetallic InAs/$Al_{0.1}Ga_{0.9}Sb$ sample, we have unambigously identified the X-line to have a different physical origin than CR, and the assignment of the X-line to the internal transition of excitons is consistent with our results.

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