Determination of Landau level lifetimes in AlGaAs/GaAs heterostructures with a ps free electron laser

W. Heiss, P. Auer, and E. Gornik
Institut für Festkörperelektronik, TU-Wien, A-1040 Wien, Austria

C. R. Pidgeon
Department of Physics, Heriot Watt University, Edinburgh EH14 4AS, Scotland

C. J. G. M. Langerak and B. N. Murdin
FOM-Instituut voor Plasmafysica, Rijnhuizen, NL 3430 BE Nieuwegein, The Netherlands

G. Weimann
Walter Schottky Institut, TU München, D 8046 Garching, Germany

M. Heiblum
Weizmann Institute of Science, Rehovot 76100, Israel

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Previous determinations of Landau level lifetimes in GaAs/AlGaAs heterostructures from saturation cyclotron resonance measurements have been confused by heating effects. We have utilized a ps free electron laser to show that for samples with sheet concentration less than $3\times10^{11}\ \text{cm}^{-2}$, true saturation of cyclotron resonance is observable at high magnetic fields, in the presence of polaron nonparabolicity. However, at higher concentrations, the polaron is screened and saturation is no longer possible. At low magnetic fields (i.e., long wavelengths) where the polaron nonparabolicity is negligible, saturation is not possible for any sheet density. It is confirmed that the lifetime of the first excited Landau level has an inverse dependence on carrier density. © *1995 American Institute of Physics.*

Saturation spectroscopy is a well established tool for the determination of electronic lifetimes in excited states. However, for AlGaAs/GaAs heterostructures, there are contradictory reports about the possibility of achieving saturation of the cyclotron resonance absorption. Helm *et al.*[1] reported a partial saturation of the cyclotron resonance absorption. By contrast, Rodriguez *et al.*[2] concluded that electron heating occurs when the cyclotron resonance is probed at high laser intensities. Maran *et al.*[3] reported saturation in heterostructures with a sheet density N_s lower than $7\times10^{10}\ \text{cm}^{-2}$. Saturation of the cyclotron resonance transition was also observed in coupled quantum well samples with carrier concentrations lower than $1\times10^{11}\ \text{cm}^{-2}$.[4]

In order to distinguish where heating effects dominate, we have utilized a ps free electron laser (FELIX) for the present saturation cyclotron resonance measurements in AlGaAs/GaAs heterostructures with various carrier concentrations. We focus on the question of whether the illumination with high intensity radiation is causing heating of the two dimensional electron gas or is saturating the cyclotron resonance transition. In all previous work,[1–4] the intensity dependence of the cyclotron resonance was investigated in the steady state, in the sense that the duration of the laser pulses was longer than the expected lifetime in the excited Landau level.

In a ladder of equidistant Landau levels no saturation can be achieved. In such a system, the increase of the laser intensity leads to the population of an increasing number of excited Landau levels. In AlGaAs/GaAs heterostructures, a nonequidistant spacing between the Landau levels (LL) is produced principally by the polaron effect. The resonant polaron effect leads to a significant increase of the effective mass, when an LL is close to a virtual state, which is formed by the $n=0$ state plus the excitation of the optical phonons ($\hbar\omega_{\text{op}}=36$ meV).[5,6] So, for the $n=1$ LL, the resonant polaron effect is observed at a magnetic field around 22 T, while for the $n=2$ LL, the increase of the effective mass occurs around 11 T. Thus, at 11 T, the $n=2$ LL is significantly shifted, and the intensity dependence of the ($n=0$ to 1) cyclotron resonance absorption can be modeled within a two level system.

The rate equations for the two level system describes the temporal evolution of the carrier density $N_n(t,B)$ in the ground state ($n=0$) and in the first excited state ($n=1$):

$$\frac{dN_0(t,B)}{dt}=-\frac{I(t)}{\hbar\omega}A_0(t,B)+\frac{N_1(t,B)}{T}, \tag{1}$$

$$N_1(t,B)=N_s-N_0(t,B). \tag{2}$$

The absorption of the two dimensional electron gas in a magnetic field is written as

$$A_0(t,B)=\frac{4}{(1+\sqrt{\epsilon})^2}\frac{\text{Re}[\sigma_{xx}^{(0)}(t,B)]}{\epsilon_0 c}, \tag{3}$$

where the real part of the dynamic conductivity is written as:

$$\text{Re}[\sigma_{xx}^{(0)}(t,B)]=[N_0(t,B)-N_1(t,B)]\times\frac{e^2}{m^*}\frac{1/\tau}{1/\tau^2+(\omega_L-eB/m^*)^2}. \tag{4}$$

Within the analysis, the intensity $I(t)$ of the laser pulse is assumed to be Gaussian. The rate equations contain two parameters that have to be fitted to the experiment. These are the scattering time τ and the lifetime of the carriers in the

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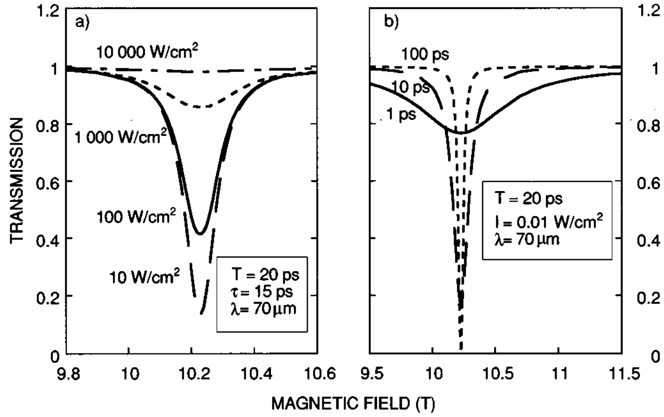

FIG. 1. (a) Theoretical cyclotron resonance transmission spectra calculated within the two level system for various laser intensities and a constant scattering time τ. A homogeneous broadening is shown. (b) Theoretical cyclotron resonance transmission spectra for various assumed values of scattering time, τ, with constant laser intensity. An inhomogeneous broadening is shown.

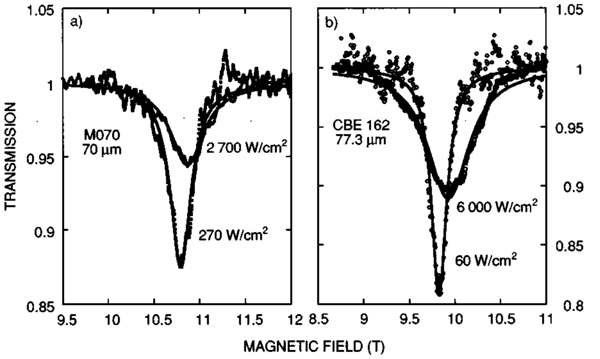

FIG. 2. (a) Experimentally determined cyclotron resonance transmission for a sheet density of 2.2×10^{11} cm^{-2} at two intensities. A homogeneous saturation behavior is observed. (b) Cyclotron resonance transmission for two intensities and a sheet density of 4×10^{11} cm^{-2}. The cyclotron resonance transition broadens inhomogeneously with increasing laser intensity.

excited state T. In heterostructures with low carrier densities,[3] the lifetime in the excited LL was found to be inversely proportional to N_1. Extrapolating this result to the maximum carrier concentration of our samples ($N_s=4\times10^{11}$ cm^{-2}, and $N_1\leqslant2\times10^{11}$ cm^{-2}), we expect a minimum lifetime of 20 ps. This value is longer than the duration of our laser pulse. In this limit the lifetime, T, in Eq. (1) is determined solely by the length of the laser pulse, and the cyclotron resonance absorption does not depend on it. Therefore, for the solution of the rate equations we set T equal to the pulse duration t_p. Most importantly, the use of a ps laser enables us to make a clear determination of τ independently of T. This has not previously been the case for "cw" measurements.

The rate equations were solved under the boundary condition $N_0(-t_p)=N_s$. The transmission $T(t,B)$ is determined from the solution of the rate equation by:[3]

$$T(t,B)=4\left[1+n_{\mathrm{GaAs}}+\mathrm{Re}\left(\frac{\sigma_{xx}^{(0)}}{\epsilon_0 c}\right)\right]^{-2}. \tag{5}$$

For a comparison with the experiment, $T(t,B)$ is integrated over time and normalized in respect of the laser intensity.

In Fig. 1(a), theoretical curves obtained from Eq. (5) for the two level system are shown for various laser intensities and a constant scattering time τ. The spectrum shows a single homogeneously broadened Lorentzian line shape. With increasing intensity the amplitude of the absorption is decreasing while the linewidth is increasing. The area under the absorption line is decreasing due to the saturation of the cyclotron resonance transition. At an intensity of 10 000 W/cm^2, the saturation is nearly complete.

By contrast, inhomogeneous broadening of the cyclotron resonance transmission would be expected if the scattering time τ is changed instead of the intensity. In Fig. 1(b), the theoretical scenario is shown for a constant intensity of 0.01 W/cm^2. At a scattering time of 100 ps, the absorption is 100% in the resonance while the linewidth is 0.05 T. With decreasing τ the absorption is reduced and the linewidth is increased drastically. In contrast to Fig. 1(a), in this plot the area under the absorption lines is not decreasing when the amplitude of the absorption becomes smaller, and the wings of the broadened lines lie progressively further outside the homogeneously broadened line.

The transmission experiments were performed with the rf linac pumped free electron laser FELIX at Rijnhuizen (the Netherlands). FELIX delivers "macropulses" with a duration of 4 μs at a repetition rate of 5 Hz. Each macropulse consists of a train of "micropulses," 20 ps long with 1 ns spacing. The samples were mounted in the center of a superconducting magnet and immersed in liquid helium. The intensity of the laser beam was controlled using well calibrated wire mesh attenuators. A black polythene filter was used to shield the sample from background radiation. The laser beam was directed onto the sample by an oversized waveguide. The radiation was measured by the broadband free electron photoconductivity in bulk InSb. Two photoconductive detectors were mounted, one in the waveguide in front of the sample as a reference and the other just behind the sample to measure the transmitted signal. We have investigated two modulation doped n-type AlGaAs/GaAs single heterostructure samples, M070 and CBE 162, of sheet densities $N_s=2.2\times10^{11}$ cm^{-2} and 4×10^{11} cm^{-2}, respectively. Both specimens were 2° wedged and polished on the back side to avoid Fabry–Perot interference within the sample.

In Fig. 2(a) the cyclotron resonance absorption is shown for sample M070 measured at a wavelength of 70 μm. The solid lines are best fits to the experimental data, which are represented by small square symbols. At an intensity of 270 W/cm^{-2}, a single Lorentzian shaped absorption line is observed with a transmission minimum at 10.8 T. The FWHM of the transition is about 0.3 T. When the intensity is increased to 2700 W/cm^2, the transmission minimum is shifted to a higher magnetic field value. This is a result of the band nonparabolicity. In addition, the amplitude of the absorption line is reduced and the FWHM is enlarged. However, the linewidth is increased in such a way that the absorption curve at high intensity lies within the absorption at low intensity. The same behavior is observed with carrier concentrations lower than $0.7\times10^{11}\ \mathrm{cm}^{-2}$.[3] By comparison of these experimental data with the results of our two level system, it is seen that a clear saturation is observed in these samples with a sheet density lower than $2.2\times10^{11}\ \mathrm{cm}^{-2}$. Our results show that measurements for carrier concentrations in this regime are not obscured by heating effects and confirm an inverse dependence of T on N_1.

The intensity dependent cyclotron resonance transmission for the sample CBE 162 measured at a wavelength of 77.3 μm is shown in Fig. 2(b). At low intensities, a narrow cyclotron absorption line is observed. When the intensity is increased, the transmission minimum is again shifted to higher magnetic fields. In this sample, by contrast, increasing the intensity by a factor of 100 produces a reduction of the absorption of only 50%. Furthermore, with increasing intensity, a dramatic increase of the linewidth is observed, characteristic of inhomogeneous broadening [as in Fig. 1(b)]. At an intensity of 6000 W/cm^2, the FWHM amounts to 0.8 T in comparison to a linewidth of 0.2 T at 60 W/cm^2. The wings of the cyclotron resonance curve at the higher intensity overlap the absorption line at lower intensity. We repeated this experiment at wavelengths of 69 and 63 μm and observed the same behavior of the cyclotron resonance absorption. Similar behavior was also reported in Ref. 2, where heterostructures with rather high electron densities were investigated. Within the two level model this observed behavior cannot be described without a variation of the scattering time τ. A change of the scattering time always means a change of the electron temperature. Thus, we conclude that in heterostructures with carrier concentrations higher than $4\times10^{11}\ \mathrm{cm}^{-2}$, electron heating is produced by increasing the laser intensity.

As mentioned above, the resonant polaron effect is essential for the formation of a two level system within a ladder of Landau levels. In Ref. 6 the density dependence of the polaron effect was studied in GaAs/AlGaAs heterostructures. From reflectivity measurements within the reststrahlen band, a strongly reduced polaron effect was observed for samples with $N_s>3.4\times10^{11}\ \mathrm{cm}^{-2}$.[6] The reason is that at values of N_s above $4\times10^{11}\ \mathrm{cm}^{-2}$, the lowest LL is almost filled, thereby suppressing the resonant part of the polaron effect by removing the final states from the virtual transitions; the inclusion of the occupation probabilities of the LLs in a ‘‘many-polaron memory-function’’ calculation shows that a combination of occupation and screening effects provides almost complete suppression of the polaron nonparabolicity at this carrier density.[7] This is in good agreement with our experiments, where we have shown that saturation of the cyclotron resonance absorption is only achieved when the electron density is definitely smaller than $4\times10^{11}\ \mathrm{cm}^{-2}$. For that reason, we conclude that the screening of the polaron effect at high sheet densities is responsible for the fact that the cyclotron resonance transition cannot be saturated in a two dimensional electron gas. For the pure sample M070 we determine an intensity-independent value of $\tau=15$ ps.

In summary, previous determinations of Landau level lifetimes have been confused by heating effects. We have shown that for samples with sheet concentrations less than $3\times10^{11}\ \mathrm{cm}^{-2}$, true saturation of cyclotron resonance is observable at magnetic fields where the polaron nonparabolicity is significant. At higher concentrations, the polaron nonparabolicity is suppressed and saturation is no longer possible; i.e., thermal heating effects begin to dominate the saturation spectra. We have made a direct determination of the scattering time $\tau=15$ ps, for a sheet concentration $2.2\times10^{11}\ \mathrm{cm}^{-2}$, and confirmed the $(N_1)^{-1}$ dependence of T_1.

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