Impurity and Landau-level electron lifetimes in n-type GaAs

G. R. Allan, A. Black, and C. R. Pidgeon
Physics Department, Heriot-Watt University, Riccarton, Edinburgh EH14 4AS, United Kingdom

E. Gornik and W. Seidenbusch
Institut fur Experimentalphysik, Universität Innsbruck, A-6020 Innsbruck, Austria

P. Colter
Avionics Laboratory, Wright Patterson Air Force Base, Dayton, Ohio 45433
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High-power cw far-infrared laser magnetospectroscopy has been used to determine impurity and Landau-level lifetimes in n-type GaAs from saturation absorption measurements. Impurity lifetimes of 30—50 ns for the $2p_+$ state and 500 ns for the $2p_-$ state are obtained for pure uncompensated material. The optical magneto-impurity effect is shown to be characteristic of highly compensated material. At higher laser intensities, saturation cyclotron-resonance absorption has been measured, and well fitted on a three-level model. The carrier-density dependence of the $N=1$ Landau-level lifetime, τ_1, has been determined from this and cyclotron emission measurements, and compared to that of InSb. It is shown to be determined by carrier-carrier scattering, and is 10 times longer for n-type GaAs than for n-type InSb over the whole range. At densities of $\sim 10^{12}$ cm^{-3}, required for possible cyclotron laser action, the measured lifetime is greater than 10 ns for n-type GaAs, implying that population inversion is achievable with interband pumping. Measurements of the intensity (carrier-density) dependence of cyclotron-resonance linewidth have been made, and are shown to be consistent with ionized-impurity scattering.

I. INTRODUCTION

High-power far-infrared (FIR) lasers enable the application of nonlinear spectroscopic methods in the far-infrared spectral range. Several investigations of nonlinear optical phenomena including the saturation of cyclotron resonance and impurity transitions in semiconductors,[1–3] two-photon absorption,[4] and second-harmonic generation[5] have been performed, using transverse-excitation atmospheric (TEA) laser-pumped systems. In a previous paper we reported on cw FIR nonlinear magneto-absorption of $1s$-$2p_+$ shallow-donor transitions in epitaxial n-type GaAs.[6] Saturation intensities much lower than deduced from earlier pulsed-laser experiments[3] and correspondingly long lifetimes of the $2p_+$ state were observed, showing that it is essential to use cw lasers in this case. Further dramatic changes of the $2p_+$-state lifetime could be attributed to a new effect, the optical magneto-impurity resonance (OMIR). Other methods that have been used to measure or infer lifetimes of Landau states in n-type semiconductors include cyclotron-resonance-induced conductivity[7] (cross modulation)[7] and far-infrared cyclotron emission under hot-electron conditions.[8] These methods are particularly useful for low densities of carriers excited into the Landau levels. For higher densities the saturation cyclotron-resonance method is suitable provided the separation between successive Landau levels is sufficiently different for the lowest ($N=0$ to $N=1$) transition to dominate. This is obviously true for InSb,[2] and we show below that, as a result of a combination of polaron and nonparabolic band effects,[9] it is also true in our case for n-type GaAs.

In our present work we have extended earlier measurements on rather highly compensated material,[6] to very pure uncompensated n-type GaAs. This has given us reliable measurements of the $2p_+$ and $2p_-$ impurity-state lifetimes and enabled us to elucidate the role of the optical magneto-impurity resonance effect. In addition, by going to higher far-infrared laser intensities we have been able to observe and measure the saturation of cyclotron resonance. The results are well interpreted on a three-level model as described below; the two-level model used successfully in previous work on InSb (Ref. 2) is inadequate here. We have used this technique for the first time, in conjunction with far-infrared emittance measurements, to determine the carrier lifetime in the first Landau level as a function of carrier density for n-type GaAs. In a way similar to the photoexcitation technique described recently,[10] we have been able to measure and interpret the dependence of carrier (momentum) scattering time on carrier density, in the $N=0$ Landau level. This result is deduced from the cyclotron-resonance linewidth. Finally, we have measured cw saturation cyclotron resonance in n-type InSb both for comparison, and to extend the earlier TEA laser work[2] to lower carrier densities.

II. EXPERIMENTAL DETAILS

Previous measurements of FIR nonlinear magnetoabsorption and photoconductivity of impurity transitions in n-type GaAs were made with epitaxial layers of about

50-μm thickness, having a donor concentration of $N_D \simeq 2\times 10^{14}$ cm^{-3} and a rather large compensation ratio ($K = N_A/N_D \simeq 0.8$, where N_A is the density of acceptors).[6] In the present FIR magnetoabsorption work we have used pure vapor-phase epitaxial n-type GaAs of extremely low compensation ratio ($N_D - N_A = 3\times 10^{14}$ cm^{-3}, $K \leq 0.1$, and thickness $\simeq 40$ μm). The sample was mounted in a metallic light pipe at the center of a superconducting solenoid and immersed in liquid helium at 4.2 K. The measurements were performed in the Faraday configuration. A high-power Edinburgh Instruments optically pumped FIR laser, operated either cw or with controlled pulse lengths, was applied using CH_3OH and other laser lines. In pulsed measurements the pulse duration was adjusted to be longer than any expected relaxation time, ensuring steady-state conditions during optical excitation. The FIR intensity in the sample was determined by a calibrated pyroelectric detector taking into account the losses of the light pipe and the reflection at the crystal surface. Due to light-pipe optics the sample was subjected to unpolarized radiation. Therefore the effective intensity was one-half of the total intensity in the sample, because circular polarized radiation only is absorbed in the Faraday configuration. Either n-type InSb or gallium-doped Ge photoconductive detectors were used, situated below the sample in the liquid-He bath. At higher intensities and magnetic fields we have measured cyclotron resonance of both n-type GaAs and n-type InSb.

The system for measuring cyclotron-resonance emission has been described previously.[11] Emitter and detector are immersed in liquid He and placed in two independent magnetic fields which can be tuned separately. Cyclotron emission is generated by applying voltage pulses to the emitter. The radiation is guided by a metallic light pipe to a narrow-band photoconductive detector. The detector signal is measured using conventional boxcar techniques. The detector consists of the same GaAs material as mentioned above. The narrow-band transition between the impurity level ($1s$-$2p_+$) of shallow impurities in a magnetic field is used for the spectral analysis. With a magnetic field up to 80 kG the energy of this transition can be tuned between 36 and 110 cm^{-1}. The linewidth measured with a Fourier spectrometer was found to be 0.25 cm^{-1}. In the experiments the detector line is set at constant magnetic field to a certain resonance frequency. By tuning the emitter magnetic field the frequency of the emitted radiation is tuned through the detector line.

III. EXPERIMENTAL RESULTS

General reviews of the FIR magneto-optical properties of shallow impurities in n-type GaAs (Ref. 12) and hot-electron properties of impurity and cyclotron resonance[13] have been given elsewhere. At low-light intensities and in the absence of an external electric field the electrons are all frozen out on the donor impurity states at low temperatures and a characteristic "hydrogenic" spectrum is obtained. In the presence of an electric field, produced either with an external source or by raising the intensity of the light itself (i.e., by the use of a laser), electrons are easily promoted into the $N=0$ conduction Landau level by impact ionization, where cyclotron resonance is observed. They can also be promoted using external visible radiation. At sufficient external electric fields, transitions between higher Landau levels ($N=1$ to $N=2$, etc.)/of reduced separation are observed, associated with the mass increasing with polaron and nonparabolic-band corrections.[9] The corresponding line splittings are about 10 times larger than a very small spin splitting observed previously[14,15] in the absence of an electric field, and are seen by us (see below) at the high laser intensities used.

Typical transmission data obtained by sweeping the magnetic field for a variety of fixed laser wavelengths at different intensities are shown for $1s$-$2p_+$ impurity transitions in Fig. 1, and at somewhat higher intensities for cyclotron resonance in Fig. 2. The impurity lines show strong saturation, associated with long lifetimes, and disappear at high intensities. However, in the present work the OMIR effect, observed previously in highly compensated material,[6] is not evident. At higher laser intensities the cyclotron-resonance line appears, grows in strength, and finally saturates; at the highest intensities a high-field should appears associated with the next-higher Landau-level transition ($N=1$ to $N=2$). The separation is in good agreement with that expected.[9]

The peak absorption coefficient α is calculated from the transmission data by using $\alpha = [\ln(I'/I'') + (rI''/I')^2 - r^2]/d$, where r is the reflectance of each sample surface, d is the thickness, and I' and I'' are the output intensities off and on resonance. The intensity dependence of α for $1s$-$2p_+$, $1s$-$2p_-$ and cyclotron-resonance transitions is shown in Figs. 3, 4, and 5, respectively. The solid curves show the best theoretical fit as described in Sec. V. In order to determine the lifetime, τ_{eff}, from the saturation intensity, $I_s = \hbar\omega/2\sigma\tau_{\text{eff}}$, it is necessary to determine the absorption cross section, σ [$=\alpha/(N_D - N_A)$]. This we find to be $\sigma = 1.8\times 10^{-12}$ cm^2 for $1s$-$2p_+$ transitions, in good agreement with other work.[10] In our previous work on magnetoabsorption[6] σ was underestimated by a factor of ~ 3 as a result of an error in the determination of

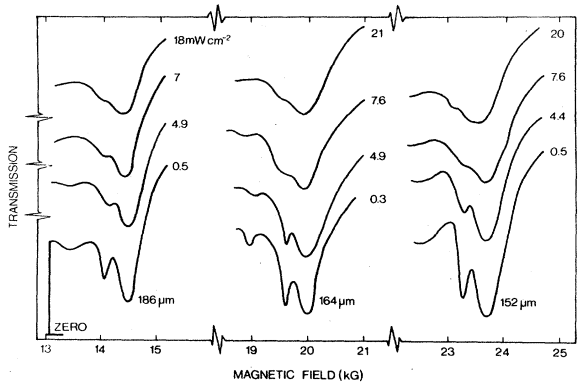

FIG. 1. $1s$-$2p_+$ magnetoabsorption lines in uncompensated n-type GaAs ($N_D - N_A = 3\times 10^{14}$ cm^{-3}, thickness 40 μm) as a function of intensity at three different wavelengths, $T=4.2$ K. Fine structure associated with central cell corrections (Ref. 21) is not included in the analysis. The transmission zero is that appropriate to circularly polarized light.

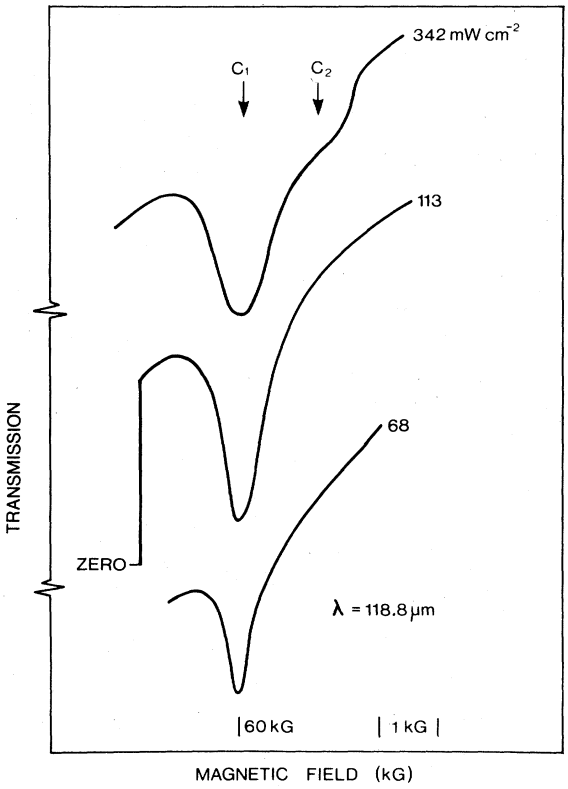

FIG. 2. Cyclotron-resonance absorption in n-type GaAs as a function of laser intensity at 118.8 μm. The top trace shows the $N=0$ to $N=1$, and $N=1$ to $N=2$ transitions (C_1 and C_2). The transmission zero is that appropriate to circularly polarized light.

(N_D-N_A). This resulted in τ_{eff} values that were of ~ 3 times too big (see Table I of the present work). In the case of cyclotron resonance, σ depends upon magnetic field as described in Sec. IV.

Emittance measurements were made as described above and elsewhere,[9,11] and the strength of the peak cyclotron emission used to determine the $N=1$ Landau-level lifetime in the low-density region. The analysis and results are described in Sec. V.

IV. THEORY AND DISCUSSION

A. Impurity resonance

A plot of the theoretically computed impurity and Landau levels[16] as a function of magnetic field is shown in Fig. 6. The impurity and cyclotron transitions are indicated for the different laser wavelengths used.

We consider first the $1s$-$2p_+$ transitions. We interpret our results with a three-level model[6] where an electron excited into the $2p_+$ state (rate X_0) may either relax directly into the $1s$ ground state (rate T_0), or be transferred directly to the conduction band (rate X_1) and then be captured by an ionized donor (rate T_1 times the concentration of

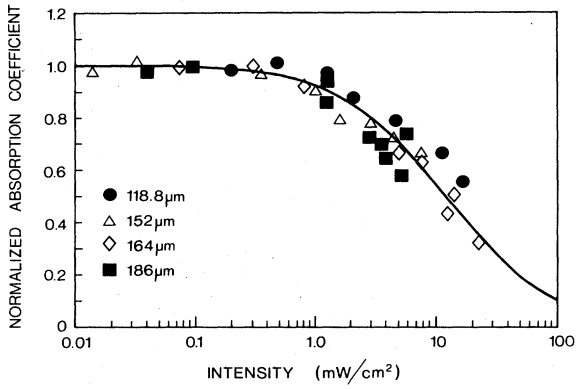

FIG. 3. Intensity dependence of $1s$-$2p_+$ peak absorption in uncompensated n-type GaAs at a variety of different wavelengths. The solid line shows the mean best fit from Eq. (7). The actual lifetimes deduced are shown in Table I.

ionized donors). The situation is shown schematically in Fig. 7 for the case of 24 kG (152 μm), where the $2p_+$ state is at a higher energy than the $N=0$ Landau level. Also shown are the $2p_-$ and $N=1$ Landau levels involved in the OMIR (see below). The rate equations are given by

$$dn/dt = X_1 n_{D^*} - T_1 n p_D \ , \tag{1}$$

$$dn_{D^*}/dt = X_0 n_D - T_0 n_{D^*} - X_1 n_{D^*} \ , \tag{2}$$

$$dn_D/dt = -X_0 n_D + T_0 n_{D^*} + T_1 n p_D \ , \tag{3}$$

where n, n_D, n_{D^*}, and p_D are the concentrations of electrons in the $N=0$ Landau subband, $1s$ ground state, and $2p_+$ excited state and of ionized donors, respectively. At low temperatures the excitation rate is given by $x_0=\sigma I/\hbar\omega$, where σ, I, and $\hbar\omega$ are the optical cross section, radiation intensity, and photon energy. The relaxation constant may be written $T_0=\bar{T}_0+\sigma I/\hbar\omega$, where the first term refers to phonon emission and the second to stimulated photon emission (we ignore spontaneous emis-

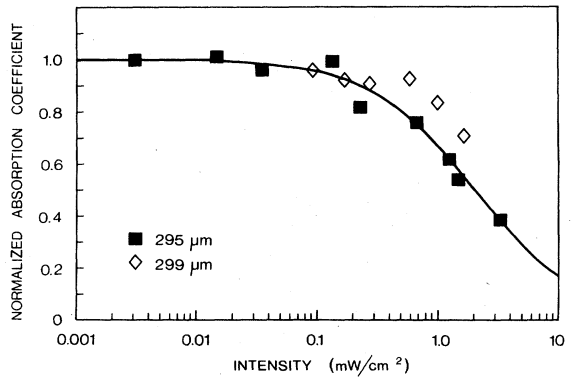

FIG. 4. Intensity dependence of $1s$-$2p_-$ peak absorption in uncompensated n-type GaAs. The solid line shows the best fit from Eq. (7). This corresponds to a lifetime of $\tau_{2p_-} \simeq 300$ ns.

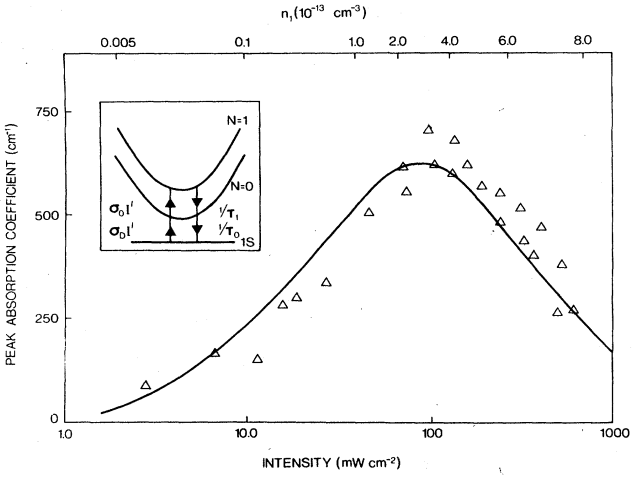

FIG. 5. Intensity dependence of peak cyclotron-resonance absorption in n-type GaAs ($P_A=3\times10^{14}$ cm^{-3}) at 118.8 μm. The triangles show the experimental points. The solid line is the best fit of the rate equation model of Eq. (15) with $\tau_1=0.8$ ns and $\sigma_D\tau_0=0.5\times10^{-24}$ m^{2}s (see text). The transitions are shown schematically (inset), and the computed values of n_1 from Eq. (13).

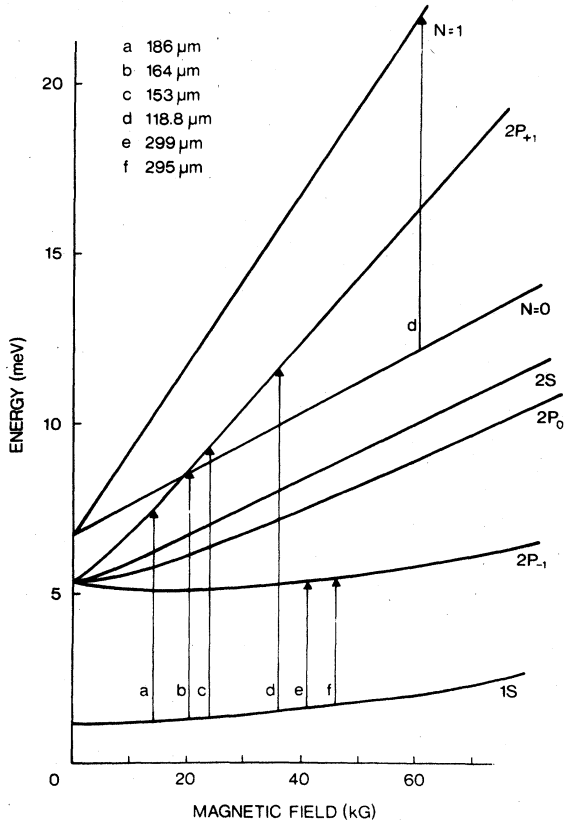

FIG. 6. Plot of magnetic field dependence of shallow impurity states and Landau levels for n-type GaAs [after Ref. (16)]. $1s$-$2p_+$, $1s$-$2p_-$, and cyclotron transitions are shown at a variety of laser wavelengths used experimentally: (a) 186, (b) 164, (c) 153, (d) 118.8, (e) 299, and (f) 295 μm.

sion). Depending on whether the $2p_+$ state is below or above the $N=0$ Landau subband, the transfer rate X_1 of electrons to the band is governed by photon absorption or emission, or by tunnelling. The band—to—ground-state recombination is through s states, given by $T_1=\langle v\rangle\sigma_c$, where $\langle v\rangle$ is the average velocity of electrons and σ_c the capture cross section of ionized donors.[17–19]

Under steady-state conditions, taking into account the conservation of total donor number, $N_D=n_D+n_{D^*}+p_D$, and charge, $P_A=N_D-N_A=n_D+n_{D^*}+n$, the carrier concentrations are given by

$$n_D=\frac{(T_0+X_1)(P_A-n)}{T_0+X_0+X_1}\ , \tag{4}$$

$$n_{D^*}=\frac{X_0(P_A-n)}{T_0+X_0+X_1}\ , \tag{5}$$

$$T_1 n(N_A+n)=\frac{X_0X_1(P_A-n)}{T_0+X_0+X_1}\ . \tag{6}$$

In the linear limit, where $n<N_A$, this gives for the ($1s$-$2p_+$) absorption coefficient

$$\alpha=\sigma(n_D-n_{D^*})=\alpha_0/(1+I/I_s)\ , \tag{7}$$

where

$$I_s=\frac{\hbar\omega}{2\sigma\tau_{\rm eff}}=\frac{\hbar\omega}{2\sigma}\frac{\bar{T}_0+X_1}{1+(X_1/2T_1N_A)}\ . \tag{8}$$

TABLE I. Lifetime and saturation intensity of $2p_+$ state in n-type GaAs obtained from measurement of saturation of $1s$-$2p_+$ transition. The OMIR is evident for the compensated material (Ref. 6) (see text) but not for the present uncompensated material.

		Uncompensated $N_D-N_A=3\times10^{14}$ cm^{-3}		Compensated $N_D-N_A\simeq1\times10^{14}$ cm^{-3}	
λ (μm)	B (kG)	$\tau_{\rm eff}$ (ns)	I_s (mW cm^{-2})	$\tau_{\rm eff}$ (ns)	I_s (mW cm^{-2})
118.8	36	14	25	14	26
152	24	27	17	9	22
164	20	36	12	40	8
186	14	38	7	6	40

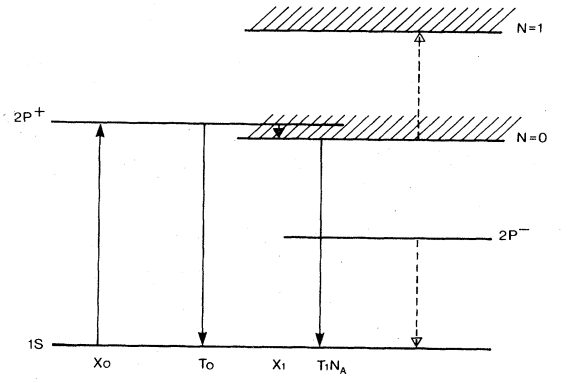

FIG. 7. Schematic representation of $1s$, $2p_+$, and $N=0$ Landau subband three-level system for magnetic field 24 kG. Transition rates are described in the text. $2p_-$ and $N=1$ levels responsible for the OMIR are also shown.

The intensity dependence of α for a variety of different wavelengths is shown in Fig. 3, together with the best-fitted theoretical curves from Eq. (7). Good fits are obtained yielding values for τ_{eff} from Eq. (8). Results are summarized in Table I. Strong saturation is observed, but as stated earlier, we do not see the OMIR which appears to require strongly compensated material (i.e., a high value of N_A and hence concentration of ionized donors, p_D) for its manifestation.[6] The magneto-impurity resonance effect[20] occurs under hot-electron conditions, due to a scattering process in which resonant heating of conduction electrons from the $N=0$ to $N=1$ Landau level is caused by the deexcitation of the hot-electron population in the $2p_-$ states to the $1s$ ground state (Fig. 7), and is clearly more probable for high values of p_D. In the compensated material, the lifetimes at wavelengths corresponding to MIR fields ($\Delta E=n\hbar\omega_c$, yielding $B=12$ and 24 kG for the first two resonances) were much shorter than the off-resonant case (at $B=20$ kG). These are shown for comparison in Fig. 1. τ_{eff} in the off-resonant case is comparable to τ_{eff} for the uncompensated material as expected. At the highest energy (magnetic field) a shorter lifetime is observed in both cases which is probably associated with a fast (optical-phonon) deexcitation process associated with the hot-electron distribution in the conduction band.

In interpreting the meaning the τ_{eff} in Eq. (8) we can look to other work on n-type GaAs, in addition to the important result we now have—viz. in the absence of the OMIR, τ_{eff} is independent of the degree of compensation (i.e., of N_A). The direct $2p_+$-to-$1s$ phonon lifetime is calculated to be of the order of 10 μs.[3,19] Thus, $\tau_{\text{eff}}<\tau_{2p_+,1s}$, and we measure $\tau_{\text{eff}}\leq(X_1)^{-1}+(2T_1,N_A)^{-1}$; that is, the saturation of intensity we determine gives the lifetime for transfer of electrons from the $2p_+$ state via the conduction band to the $1s$ ground state. However, we have shown above that it is also independent of N_A. Thus, the rate-limiting process is the transfer of electrons into the conduction band and we determine $\tau_{\text{eff}}=(X_1)^{-1}$.

The observation of the OMIR in compensated material implies a substantial buildup of hot-electron population in the $2p_-$ state, in turn requiring along lifetime. We have confirmed this by measuring the saturation of the $1s$-$2p_-$ transition directly. Results with the best-fitted theoretical curve from Eq. (7) are shown in Fig. 4. As expected a very long lifetime, $\tau_{\text{eff}}=0.5$ μs, is obtained.

B. Cyclotron-resonance absorption and emission

As mentioned previously, with the high laser intensities available we have found it possible both to observe and saturate the cyclotron-resonance absorption. The dependence of α on intensity for n-type GaAs is shown using the 118.8-μm CH_3OH laser line in Fig. 5. The solid line shows the best theoretical fit from a three-level model as follows. The levels and transitions are shown in the Fig. 5 inset.

We denote by n_D, n_0, and n_1 the concentration of electrons in the donor ground state, the $N=0$ and 1 Landau levels, respectively. In the steady state these are given by the following rate equations:

$$\sigma_D I'(n_D-n_0)=n_0/\tau_0\ , \tag{9}$$

$$\sigma_0 I'(n_0-n_1)+n_0/\tau_0=\sigma_D I'(n_D-n_0)+n_1/\tau_1\ , \tag{10}$$

and

$$\sigma_0 I'(n_0-n_1)=n_1/\tau_1\ , \tag{11}$$

where $\sigma_D I'$ and $\sigma_0 I'$ are the respective excitation rates for impact ionization and cyclotron-resonance transitions, with $I'=I/\hbar\omega$. τ_0 and τ_1 are the lifetimes of the $N=0$ and 1 Landau states. Direct transitions between the impurity ground state and $N=1$ Landau level are assumed negligible.[7] Using the fact that the total carrier concentration is

$$P_A=n_D+n_0+n_1\ , \tag{12}$$

and rearranging, we have

$$n_1=\frac{P_A}{[1+(2+1/\sigma_D I'\tau_0)(1+1/\sigma_0 I'\tau_1)]}\ , \tag{13}$$

and

$$n_0=n_1(1+1/\sigma_0 I'\tau_1)\ . \tag{14}$$

Thus, the peak cyclotron-resonance absorption coefficient is given by

$$\alpha=\sigma_0(n_0-n_1)=n_1/I'\tau_1$$

$$=\frac{P_A}{I'\tau_1[1+(2+1/\sigma_D I'\tau_0)(1+1/\sigma_0 I'\tau_1)]}\ . \tag{15}$$

In fitting the expression of Eq. (15) to the experimental points of Fig. 5 we take advantage of the fact that at low intensities α is almost independent of τ_1, i.e., $\alpha\simeq\sigma_0\sigma_D I'\tau_0 P_A$, whereas at high intensities it is almost independent of $\sigma_D\tau_0$. Then, using the result obtained by other workers[7] that $\sigma_0=4\times10^{-18}(\omega_c\tau)$ m^2, where

$\omega_c\tau=800$ in our case (see below), we obtain the best overall fit with $\sigma_D\tau_0=0.5\times10^{-24}$ m^{2}s and $\tau_1=0.8\pm0.2$ ns. This is shown by the solid line in Fig. 5 together with the carrier density in the $N=1$ Landau level obtained from Eq. (13). At the highest intensities the model should be expanded further to include the experimental observation (Fig. 2) that about $\frac{1}{6}$ of the carriers participate in the higher ($N=1$ to $N=2$) transition. To a first approximation this can be treated by reducing the total concentration, P_A, by this amount. This then gives the result that τ_1 varies from 1 to 0.5 ns in the range $n_1=(1-5)\times10^{13}$ cm^{-3}. This decrease with density is due to an electron-electron scattering mechanism described below. The results are shown in Fig. 8 and compared to our own cw, and previous pulsed,[2] saturation cyclotron-resonance measurements on n-type InSb. The same trend is observed for both cases but the lifetime is found to be about 10 times longer for n-type GaAs than n-type InSb.

In order to measure τ_1 in the low-density region and confirm the trend due to carrier-carrier scattering, emittance measurements were made for n-type GaAs and n-type InSb. In terms of the emitted power out P_0 and the electrical power in P_i, we have[8]

$$\tau_1\simeq\frac{P_0n_0\eta^2}{P_in_1W_{10}}\ , \tag{16}$$

where η is the refractive index and W_{10} is the transition probability

$$W_{10}=\frac{\eta e^2\mu_0\omega_c^2}{3c\pi m^*}\ . \tag{17}$$

The ratio n_0/n_1 is determined experimentally by the ratio of the strengths of emittance peaks for the $N=0\rightarrow1$ and $1\rightarrow2$ cyclotron transitions. Results for τ_1 as a function of n_1 for n-type InSb and n-type GaAs are shown in Fig. 8. Very good agreement is obtained with the cyclotron-resonance absorption results, with both materials showing a linear decrease of τ_1 with increasing n_1 above a certain value. The behavior can be explained by two mechanisms: At low concentrations acoustic phonon scattering limits the lifetime at a nearly constant value for all materials. With increasing density a concentration-dependent scattering mechanism sets in.[2] Scattering of 2 electrons in the $N=1$ level puts one in the $N=0$ level and one in the $N=2$ level. If the $N=2$ level is above the optical-phonon energy also this electron is rapidly ($\sim10^{-12}$) transferred to the lowest level. If the $N=2$ level is below the optical-phonon energy (as for GaAs) the scattering is somewhat less effective. This is most likely the reason that the observed lifetimes are considerably longer for GaAs than for InSb. The observed short electronic lifetime in InSb limits the external quantum efficiency to a value of 10^{-4}. In GaAs quantum efficiencies up to 5×10^{-3} are found. From Fig. 9, the question as to whether population inversion can be achieved by an optical pumping process across the gap can be answered. The band-to-band lifetimes are on the order of 10^{-8} s for the semiconductors considered so that only GaAs has a τ_1 value above this at concentrations of 10^{12} cm^{-3}. This concentration is necessary in the excited level to obtain gain, meaning that GaAs is a candidate for obtaining population by one- or two-photon pumping across the gap.

Finally, we have measured the intensity dependence of the linewidth, ΔB, of cyclotron-resonance absorption in n-type GaAs (shown in Fig. 9) to give the inverse momentum scattering time,

$$1/\tau=\omega_c\,\Delta B/2B_c\ . \tag{18}$$

We assume that the density variation can be written[10]

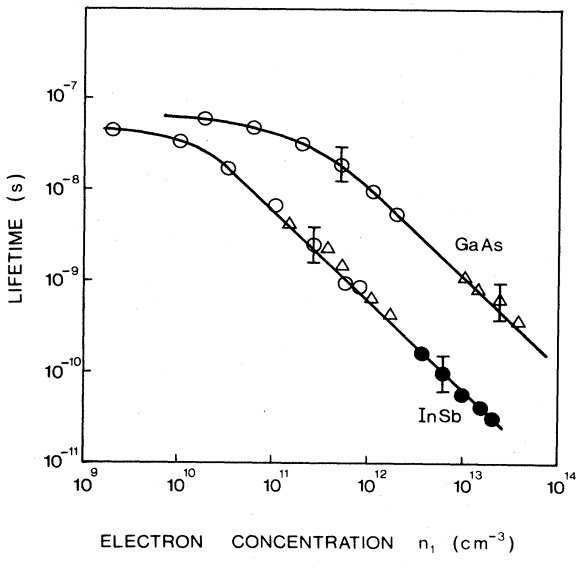

FIG. 8. Electron concentration dependence (n_1) of the $N=1$ Landau-state lifetime, τ_1, for n-type GaAs and n-type InSb. Triangles show the results of saturation cyclotron resonance, and open circles are of cyclotron emission. The solid circles are from previous work on saturation cyclotron resonance (Ref. 2).

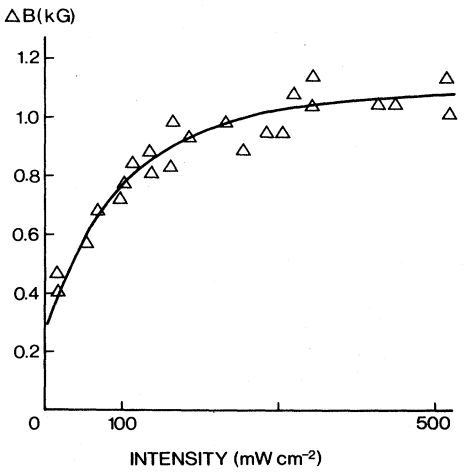

FIG. 9. Intensity dependence of cyclotron-resonance linewidth for n-type GaAs at 118.8 μm. The triangles mark the experimental points, and the solid line is an aid for the eye.

$$1/\tau = a + b(n_0 + n_1)^d , \quad (19)$$

where a is the density-independent impurity limit of $1/\tau$, and b and d are constants. Plotting $1/\tau$ against n_0+n_1 on logarithmic scales, we find (Fig. 10) a linear dependence ($d=1$) for concentrations greater than 6×10^{13} cm^{-3}, implying that carrier-carrier scattering dominates in this range. This is in accord with results for higher concentration material using the photoexcitation technique.[10]

V. CONCLUSION

We have used cw FIR laser spectroscopy to determine impurity and Landau-level lifetimes in highly pure uncompensated n-type GaAs. Lifetimes of the $2p_+$ states have been determined by saturation absorption measurements, and shown by comparison with previous work on compensated material to be dominated by the transition rate into the conduction band.[6] Times are typically of $\sim$30 to 50 ns. In addition, the OMIR effect has been shown to be strongly dependent on the presence of a high acceptor concentration, and characteristic of compensated material. It is shown that in the presence of a laser, a high concentration of hot electrons is built up in the $2p_-$ states which have even longer lifetimes, of $\sim$500 ns.

Extension to higher laser powers has enabled both the observation and saturation of the cyclotron resonance. Results are very satisfactorily explained with a three-level model, which is further justified by the observation of the next-higher ($N=1$ to $N=2$) Landau-level transition appearing as a high-field shoulder on the cyclotron-resonance line at the highest intensities—i.e., the separation between successive Landau levels decreases with increasing effective mass resulting from polaron and nonparabolic band corrections.[9] We have thus determined the lifetime of the $N=1$ Landau state, τ_1, as a function of carrier density.

Further measurements have been made of cyclotron emission as an alternative method of determining τ_1, both for comparison and to extend the results down to the low density region. Very good agreement is obtained, and the results are consistent with a phonon scattering model, at low carrier densities, being dominated by carrier-carrier scattering at higher densities. The results are compared to the present, and other, similar measurements on n-type InSb. Exactly the same concentration dependence is observed but the measured values of τ_1 are in all cases about 10 times shorter for InSb. At concentrations below 10^{12} cm^{-3}, τ_1 is greater than 10 ns for n-type GaAs, implying that cyclotron-emission laser action by interband pumping of this material is feasible; this is probably not the case for n-type InSb.

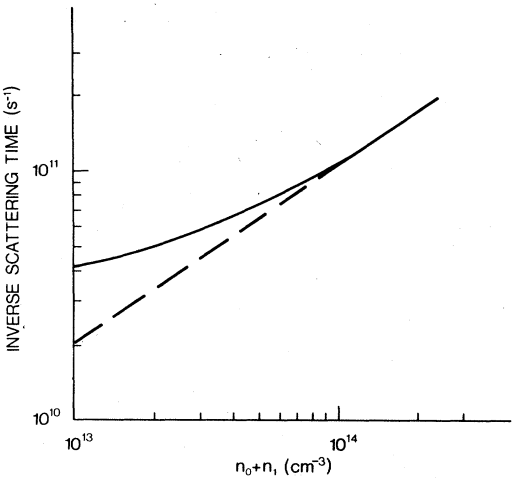

FIG. 10. The inverse cyclotron (momentum) scattering time as a function of n_0+n_1 computed from Eqs. (13), (14), and (19). The solid line shows the mean of the experimental points from Fig. 9. The dashed line corresponds to a linear dependence of $1/\tau$ on n_0+n_1, i.e., $d=1$.

Finally, the intensity dependence of the cyclotron-resonance absorption linewidth has yielded a dependence on carrier density which is consistent with ionized impurity scattering as the dominant broadening mechanism determining the momentum scattering time.

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