Study of cyclotron-resonance-induced conductivity in n-GaAs

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A study has been made of the change in the conductivity of n-GaAs under cyclotron-resonance (CR) conditions (cross modulation) at high magnetic fields. Measurements are presented of CR-induced Hall effect, CR-induced conductivity, and the CR absorption coefficient in n-GaAs, as a function of temperature (8–40 K) at three magnetic field values ($B = 6.3$, 10.5, and 13.0 T). The CR-induced Hall-effect measurements show that the change in the conductivity under CR conditions is due to a change in the free-carrier density for $B = 10.5$ and 13.0 T over the entire temperature range and for $B = 6.3$ T below 15 K. For $B = 6.3$ T above 15 K a decrease in the mobility is observed. The change in the free-carrier density is calculated with a three-level rate equation model. With this model the energy relaxation time of the photoexcited carrier can be calculated from the measured change in the conductivity and the absorption coefficient. This results in an energy relaxation time with a T^{-3} temperature dependence and times of the order of 10^{-8} s. Using this temperature dependence of energy relaxation time, the CR-induced conductivity change is quantitatively explained. The energy relaxation of the photoexcited carriers is discussed. It is believed to be a two-step process involving a quasielastic transition from the first to the zeroth Landau level followed by a subsequent relaxation to the bottom of the band by the emission of acoustical phonons. The measured energy relaxation time combined with the measured momentum relaxation time derived from the CR linewidth and from dc transport measurement shows that electron scattering in high magnetic fields is a highly elastic process. The number of interactions per unit time in which energy is transferred to the number of interactions in which only momentum is transferred varies from 10^{-3} at 40 K to 10^{-5} at 10 K.

I. INTRODUCTION

The purpose of this paper is to investigate in detail the mechanism which causes the change in the static conductivity in a semiconductor under cyclotron-resonance conditions. In the literature, this effect is often referred to as "cross modulation." The term cross modulation originates from atmospheric physics; it was found that a signal modulated with a frequency corresponding to the cyclotron-resonance frequency of the electrons in the earth's magnetic field, could be detected at another frequency if this radiation passed through the same part of the ionosphere[1,2]. This effect was explained as being due to a modulation of the conductivity of the ionosphere by a change in the carrier relaxation time because of the cyclotron-resonance absorption. In a solid, the same effect was found for the first time by Zeiger *et al.*[3]; in Ge and n-Si, a change in the static conductivity under cyclotron-resonance conditions was found. Subsequently, this technique for studying cyclotron resonance by measuring the change in the dc conductivity has been used in a number of semiconductors, i.e., InP, CdTe, CdSe, GaAs,[4] AgBr,[5] Te,[6] and InSb.[7] In addition, this method proved to be so sensitive that it is possible to make selective detectors based on cyclotron-resonance-induced conductivity (CRIC).[7] However, despite its widespread use, the underlying mechanism of CRIC has never been analyzed and understood in detail.

The first CRIC experiments by Zeiger *et al.*[3] in Ge and n-Si were performed at microwave frequencies and at temperatures where the carriers were frozen out. In order to observe a resonance signal, carriers were created with a low-intensity radiation by exciting electrons from the valence band to the conduction band. It was found in these experiments that a signal could be detected even with no applied electric field, and that for different signals, either an increase or a decrease in the conductivity could be found, and finally, that the signal reversed sign with a change of experimental parameters, such as light intensity or sample orientation. Some of these complications have been investigated by several authors. Fisher and Wagner[8] have shown that the inhomogeneity of the exciting microwave radiation, as is usually the case in a microwave cavity, can give rise to a thermomagnetic effect leading to a signal, even in the absence of a dc electric field. Subsequently, von Ortenberg[6] has shown that a similar effect can occur as a consequence of sample inhomogeneities. Gershenzon *et al.*[9] have qualitatively investigated the changes in sign of the cross-modulation signal in Ge; they showed that in the presence of carriers of opposite charge (as is the case with band-to-band carrier excitation), the changes in sign could be explained by the energy dependence of either the momentum relaxation time or the recombination time. A few years earlier it had been shown by Kaplan[10] that the sign reversals encountered by Zeiger *et al.*[3] in Ge disappeared if the carriers were created by excitation from the impurities and not by band-to-band excitation. All these investigations illustrated convincingly that the subtle complications with CRIC, as reported by Zeiger *et al.*,[3] can all be attributed to the experimental conditions. However, in all these experiments, the underlying mechanism of CRIC itself has not been analyzed. There exists only a semiempirical study by Kaplan,[10] based on the same ideas as is usually done for the free-electron photoconductive Putley detector.[7] This analysis is essentially based on a hot-electron concept where carriers are heated out of thermal equilibrium by the absorbed radiation; then the sensitivity can be calculated from the energy dependence of the mobility as derived from the deviations from Ohm's law in high electric fields. The enhanced absorption coefficient at cyclotron-resonance conditions induces an enhanced heating of the carriers. Although the possibility of a change in the free-carrier density as the origin of the conductivity change has been mentioned by some workers,[2,6,9,10] it is generally assumed (with the notable exception of Ref. 6) that a change in the carrier mobility is the origin of the conductivity change. It is one of the purposes of this paper to show experimentally that in high magnetic field CRIC in n-GaAs is caused by a change in the free-carrier density only. Preliminary results of these findings have been reported before.[11]

It is obvious that for a detailed investigation of the mechanism which is responsible for CRIC, the experimental conditions have to be chosen as simply as possible. The first step is to establish whether CRIC is caused by a change in the free-carrier density or by a change in the mobility. The second step is to measure the temperature and magnetic field dependence of the effect, and to compare these measurements with the predictions of a corresponding model. Measurements of CRIC, the power absorption, the cyclotron-resonance-induced Hall effect (CRIH), and the dc Hall effect are performed as a function of temperature (8–40 K) and magnetic field (6–13 T) in n-GaAs. The CRIH measurements are carried out in order to have a direct and independent determination of the change of the density of the free carriers alone, as compared with CRIC, which measures the combination of the mobility times the density of the carriers. The measurements are compared with calculations of the charge redistribution based on a simple three-level rate equation model. This model assumes low excitation intensities, high magnetic fields ($\hbar\omega_c > kT$, $\omega_c\tau \gg 1$, where ω_c is the cyclotron frequency and τ the scattering time) and thermally excited carriers only. The experimental conditions were chosen to suit these assumptions. As a material, n-GaAs was used because of its simple band structure (direct gap, almost constant energy-independent isotropic effective electron mass). In addition, these measurements allow a determination of the relaxation time for the carriers excited to the first Landau level[12] which can give some insight into the underlying recombination mechanism.

II. CONSIDERATIONS ABOUT CYCLOTRON-RESONANCE-INDUCED CONDUCTIVITY

At low temperatures and at high magnetic fields ($\hbar\omega_c > kT$) all free electrons at thermal equilibrium are in the lowest Landau level. In this case the relative change in the conductivity at CR conditions can be written in a most general way as

$$\frac{\Delta\sigma}{\sigma} = \frac{\Delta n}{n_0^0}\,\frac{\mu_{\mathrm{eff}}}{\mu_0^0} + \frac{\mu_{\mathrm{eff}}}{\mu_0^0} - 1\,. \tag{1}$$

Here n_0^0 is the free-carrier density and μ_0^0 the mobility in the lowest Landau level at thermal equilibrium; Δn is the change in the free-carrier density and μ_{eff} is an effective electron mobility at cyclotron-resonance conditions, introduced in a purely formal way. This mobility, effective for all free electrons, can be used to describe the change in the conductivity, whether cyclotron-resonance absorption changes the mobility of all free electrons or only of the electrons excited to the first Landau level. In the latter case, μ_{eff} is a weighted average for the different mobilities in the two Landau levels. In the limit of high magnetic fields ($\omega_c\tau \gg 1$) the Hall coefficient R_H is given by $R_H = 1/n_0^0 e$, where e is the electron charge and n_0^0 the carrier concentration. Therefore a change Δn in the carrier density due to cyclotron resonance absorption can be measured directly with the Hall effect, and if the corresponding conductivity change is measured as well, the relative change in the mobility $\mu_{\mathrm{eff}}/\mu_0^0$ can be determined with the use of Eq. (1).

Usually the carriers in a semiconductor under cyclotron-resonance conditions excited to higher Landau levels will not be in thermal equilibrium with all the other carriers or with the phonon system, acting as a heat bath. The entire electronic system will then move to a new equilibrium state. For low excitation intensities and empty excited states these electrons will hardly interact with each other, and an effective temperature concept, as is mostly used for hot electrons in semiconductors, cannot be applied in this situation. In principle, the charge redistribution resulting from cyclotron-resonance absorption has to be calculated by taking into account all energy levels and all transition rates involved. A three-level model system will be used to analyze the experimental results (Fig. 1) with the donor ground state, the zeroth and the first Landau level as the relevant energy levels. At thermal equilibrium, without radiation, there are n_{1s}^0 electrons in the donor level, n_0^0 electrons in the lowest Landau level, while $n_1^0=0$ ($\hbar\omega_c > kT$). With radiation, the rate equations for a given magnetic field and temperature are given by

$$\frac{dn_{1s}}{dt} = -t_{1s\text{-}0}^{-1} n_{1s} + t_{0\text{-}1s}^{-1} n_0 ,$$
$$\frac{dn_0}{dt} = t_{1s\text{-}0}^{-1} n_{1s} - t_{0\text{-}1s}^{-1} n_0 - W n_0 , \qquad (2)$$
$$\frac{dn_1}{dt} = W n_0 - t_{1\text{-}0}^{-1} n_1 .$$

Here, W is the generation rate due to cyclotron resonance excitation, and $t_{1\text{-}0}^{-1}$ the relaxation rate between the two Landau levels; $n_{1s'}$, n_0, and n_1 are the electron densities under cyclotron-resonance conditions on the donor, the $N=0$, and the $N=1$ Landau level, respectively. If it is assumed that the thermal generation and relaxation rates $t_{1s\text{-}0}^{-1}$ and $t_{0\text{-}1s}^{-1}$ are unaffected by the cyclotron-resonance absorption, which is realistic as long as the number of carriers excited from the $N=0$ to the $N=1$ level is small compared to the total number of carriers thermally present in the $N=0$ level (low intensity of the exciting radiation), the change in the free-carrier density Δn in the steady state can be calculated from the set of Eq. (2). Using the condition of charge conservation $n_{1s}^0 + n_0^0 = n_{1s} + n_0 + n_1 = N_D - N_A$ (N_D and N_A are the donor and the acceptor density), one gets

$$\Delta n = n_1 \frac{N_D - N_A - n_0^0}{N_D - N_A} . \qquad (3)$$

The number of excited carriers n_1, is given by the third rate equation (2) in terms of W, n_0, and $t_{1\text{-}0}^{-1}$. The product Wn_0 is related to the absorption coefficient α, the radiation intensity I, and the energy of the photon $\hbar\omega_c$ by

$$W n_0 = I\alpha/\hbar\omega_c \qquad (4)$$

with

$$I = I_0 \frac{1}{\alpha d}(1 - e^{-\alpha d}) , \qquad (5)$$

which for $\alpha d \ll 1$ (small sample thickness d) reduces to the incident radiation intensity I_0. Combining Eqs. (4) and (5), one gets

$$n_1 = \frac{1}{d}\frac{I_0}{\hbar\omega_c}(1 - e^{-\alpha d}) t_{0\text{-}1} . \qquad (6)$$

The relative conductivity change due to cyclotron resonance absorption of Eq. (1) can finally be written as

$$\frac{\Delta\sigma}{\sigma} = \left(\frac{1}{d}\frac{I_0}{\hbar\omega_c}(1 - e^{-\alpha d}) t_{0\text{-}1} \frac{N_0 - N_A - n_0^0}{n_0^0(N_D - N_A)}\right)\frac{\mu_{\text{eff}}}{\mu_0^0} + \frac{\mu_{\text{eff}}}{\mu_0^0} - 1 . \qquad (7)$$

The only unknown parameter left in Eq. (7) is the relevant energy relaxation time $t_{1\text{-}0}$ of the first Landau level, all other parameters can be measured separately. Therefore it is possible to determine the Landau-level lifetime $t_{0\text{-}1}$ directly with the help of Eq. (7).

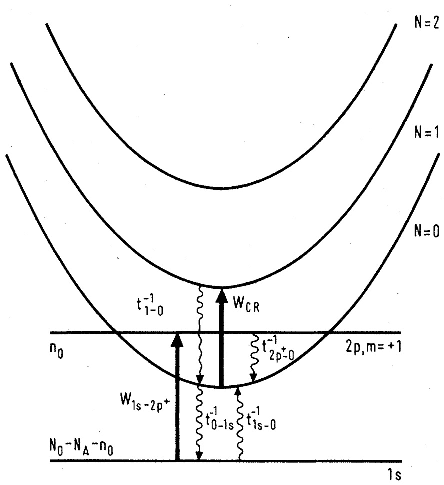

FIG. 1. Schematic energy-level structure of the GaAs conduction band and the hydrogenic donor states in a magnetic field.

III. EXPERIMENTAL DETAILS

Hall measurements were performed on an electrically symmetric cloverleaf shaped sample using the van der Pauw method. Due to the small sample area of the cloverleaf sample (1×1 mm^2), another sample (7×7 mm^2) from the same batch had to be used for the transmission measurements. Both samples had very similar electrical properties, shown in Table I. A comparison of the dependence of the resistance as a function of the magnetic field and temperature showed that the two samples behaved essentially identically. Therefore the magnetic field and temperature dependence of the free-carrier density and the mobility determined from Hall-effect measurements on the Hall sample were used to analyze the data for both samples. It should be noted that the limit of high magnetic fields ($\omega_c\tau \gg 1$) is reached for fields bigger than 5 T,[13] and consequently the Hall coefficient is given by $1/n_0^0 e$ for these fields.

The samples were tightly glued to a brass block

TABLE I. Sample characteristics.

	Hall sample			Transmission sample		
T (K)	n (10^{15} cm^{-3})	μ (cm^2/V s)	d (μm)	n (10^{15} cm^{-3})	μ (cm^2/V s)	d (μm)
300	1.50	7204	14.3	1.63	7610	19.1
77	1.40	44700		1.55	51520	

inside a variable-temperature cryostat of the exchange gas type to prevent heating of the sample by the far-infrared radiation. The contacts were carefully shielded from the radiation to avoid any photocurrent due to junctions in the contact area. The sample was biased with a constant current source, and the signal was detected with high input lock-in amplifiers operated in the differential input mode (mandatory for Hall measurements). In all experiments an increase in the conductivity due to cyclotron resonance was observed, and the signal was proportional to the bias voltage over the sample and to the power of the far-infrared radiation (FIR) for electric fields up to 2 V/cm and for FIR power levels up to 200 μW. The electric field over the sample was always less than 0.5 V/cm during the experiments, in order to be in the Ohmic region of the $I-V$ characteristic. No signal could be detected in the absence of an electric field over the sample.

The radiation was guided to the sample by a light pipe system. The FIR power level was calibrated with a pyroelectric detector. The transmitted radiation was detected with a Si bolometer cooled with liquid helium, and the total power level was monitored simultaneously with the pyroelectric detector. Actual power levels of the radiation at the sample (incorporating the measured losses of the light guiding system) were between 5 and 10 μW.

An optically pumped far-infrared laser system was used to generate the far-infrared radiation. Three different wavelengths were employed in the present experiments, $\lambda = 70.6$ and 118.8 μm with CH_3OH as active medium, and $\lambda = 57$ μm with CH_3OD.[14] The necessary high magnetic fields were generated by a Bitter coil of the Nijmegen High Magnetic Fields Installation[15] producing a maximum field of 15 T in a 6-cm bore with a 6-MW energizing system.

The effective mass determined from the resonance position (Table II) is $m^* = 0.069 m_0$. This value is somewhat larger than the most accurate determination of the effective mass at the bottom of the band of n-GaAs[17]; the deviation is caused by nonparabolicity and plasma effects, but the agreement with the literature values is sufficiently accurate to identify the observed transition as cyclotron resonance.

IV. RESULTS AND DISCUSSION

A. Charge carrier statistics

The parameters, characteristic for the material as N_D (donor density), N_A (acceptor density), and the ionization energy ΔE, can be derived from the usual analysis of the measurements of the Hall coefficient over a wide range of temperatures.[16] In addition, N_D and N_A can also be determined from an analysis of the temperature dependence of the Hall mobility at temperatures, where ionized impurity scattering is important, using the Brooks-Herring equation.[16] This analysis was performed on the measurements shown in Fig. 2 and resulted in an ionization energy $\Delta E = 2.54$ meV and densities of $N_D = 2.2 \times 10^{15}$ cm^{-3} and $N_A = 6.3 \times 10^{14}$ cm^{-3}. Calculations based on the hydrogen model lead to a donor depth of 5.72 meV. This difference between the observed ionization energy and the calculated donor depth can be explained by a broadening of excited donor states into a quasicontinuum adjacent to the band continuum, and the experimental values found for N_D and ΔE are in agreement with values found in the literature for the ionization energy as a function of the donor density.[16]

Owing to the magnetic field dependence of the donor states, the ionization energy is magnetic field dependent as well.[17-19] In order to determine this energy as a function of magnetic field, the carrier density was measured as a function of the magnetic field and the temperature as shown in Fig. 3. Incorporating the magnetic field dependence of the effective density of states, one gets for $\hbar\omega_c > kT$

$$\frac{n_0^0(N_A + n_0^0)}{N_D - N_A - n_0^0} = \frac{N_c \theta}{g_s} \exp\left(-\frac{\Delta E}{kT}\right), \tag{8}$$

where $\theta = \hbar\omega_c/kT$, $N_c = 2(2\pi m^* kT/\hbar^2)^{3/2}$, the ef-

TABLE II. Observed resonance magnetic field as a function of frequency.

Wavelength (μm)	CR transmission minimum (T)
118.8	6.3
70.6	10.5
57.0	13.0

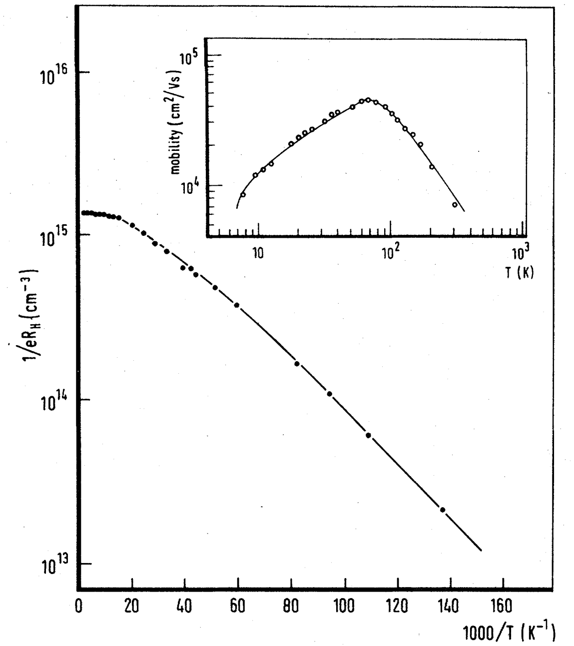

FIG. 2. Measured temperature dependence of the Hall coefficient and the Hall mobility (inset) of the Hall sample at a magnetic field of 0.5 T.

fective density of states in the conduction band at zero magnetic field, and $g_s = 2$ is the spin degeneracy factor for n-GaAs. Equation (8) is shown as the solid lines in Fig. 3. The values for the ionization energy $\Delta E(B)$ which follow from fitting Eq. (8) to the data in Fig. 3 are also presented as a function of the magnetic field in Fig. 3. One gets for fields above 3 T a magnetic field dependence of the ionization energy of $\Delta E \propto B^{0.39}$, which is very close to the $B^{1/3}$ dependence as calculated by Yafet, Adams, and Keyes[17] for the $1s$ state using the hydrogen model. At low magnetic fields, this magnetic field dependence is no longer obeyed. These data are in qualitative agreement with earlier measurements of the ionization energy in n-GaAs as a function of magnetic field.[20,21]

B. Cyclotron-resonance-induced hall effect

With the help of Eq. (1) it is possible to separate the contributions to CRIC due to a change in the mobility from the contribution due to a change in the free-carrier density by measuring the conductivity together with the Hall effect under cyclotron-resonance conditions. The results of the CRIH measurements are shown in Fig. 4 together with the relevant definition of the voltages V_H and V_I. Figure 4(b) shows peaks due to the $1s$-$2p^+$ donor transition and to cyclotron resonance in the spectrum at $\lambda = 70.6$ μm. The usual checks for Hall measurements, i.e., reversing the current and the field, were carried out and are illustrated in Fig. 4(b). It is shown that ΔV_H is caused by a change in the Hall coefficient only.

The relative change in the free-carrier density is proportional to $\Delta V_H/V_H$. The relative change in the conductivity, which also contains a contribution due to a change in the mobility, is proportional to $\Delta V_I/V_I$. Therefore it is useful to compare $\Delta V_H/V_H$ with $\Delta V_I/V_{I'}$, as is shown in Fig. 4(c). The results for the CR signal can directly be compared with the results for the donor transition, as the origin of the photoconductivity for the $1s$-$2p^+$ transition is clear and well understood. The donor transition involves an excitation from the $1s$ to the $(2p, m=+1)$ level ($W_{1s\text{-}2p^+}$ in Fig. 1) above the GaAs conduction band at the magnetic field values present,[22,23] followed by a partial relaxation from the $2p^+$ state to the conduction band ($t_{2p^+\text{-}0}$) thus increasing the free-carrier density only, with no associated mobility effect. Therefore the $1s$-$2p^+$ signal forms a suitable reference for the analysis of the CR signal. It is concluded that if $(\Delta V_H/V_H)/(\Delta V_I/V_I)$ is the same for both the CR and the donor transition, both signals are caused by a change in the free-carrier density only; whenever the CR transition ratio deviates, the difference is attributed to an associated change in the relevant mobility.

Figure 4(c) shows that for $\lambda = 57$ μm, the ratio $(\Delta V_H/V_H)/(\Delta V_I/V_I)$ for the CR and for the donor transition are equal and independent of the temperature. An identical result was obtained for $\lambda = 70.6$ μm (not shown here). However, for $\lambda = 118.8$ μm, a deviation from this behavior is observed as shown in Fig. 4(c). In this case, the ratio $(\Delta V_H/V_H)/(\Delta V_I/V_I)$ for the donor transition remains constant as a function of the temperature (as to be expected for a pure "Δn effect"), but for temperatures below 15 K, the corresponding ratio for the CR transition deviates from that of the donor transition. These results show that for $B = 13.0$ T ($\lambda = 57$ μm) and $B = 10.5$ T ($\lambda = 70.6$ μm) at all temperatures investigated, and for $B = 6.3$ T ($\lambda = 118.8$ μm) for temperatures above 15 K, CRIC is caused by a change in the free-carrier density only, but for the lower field below 15 K a mobility decrease is observed under cyclotron-resonance conditions. The lower curves in Fig. 4(c) show the ratios $(\Delta V_H/V_H)_{\mathrm{CR}}/(\Delta V_H/V_H)_{1s\text{-}2p^+}$ and $(\Delta V_I/V_I)_{\mathrm{CR}}/(\Delta V_I/V_I)_{1s\text{-}2p^+}$ and illustrate that the simple ratio $\Delta V/V$ of the two different transitions in the same configuration is strongly temperature dependent.

It should be noted that if only a change in the free-carrier density is involved, the ratios $(\Delta V_H/V_H)/(\Delta V_I/V_I)$ should be unity, since in that case both the numerator and the denominator are equal to $\Delta n/n_0^0$. However, as can be seen from

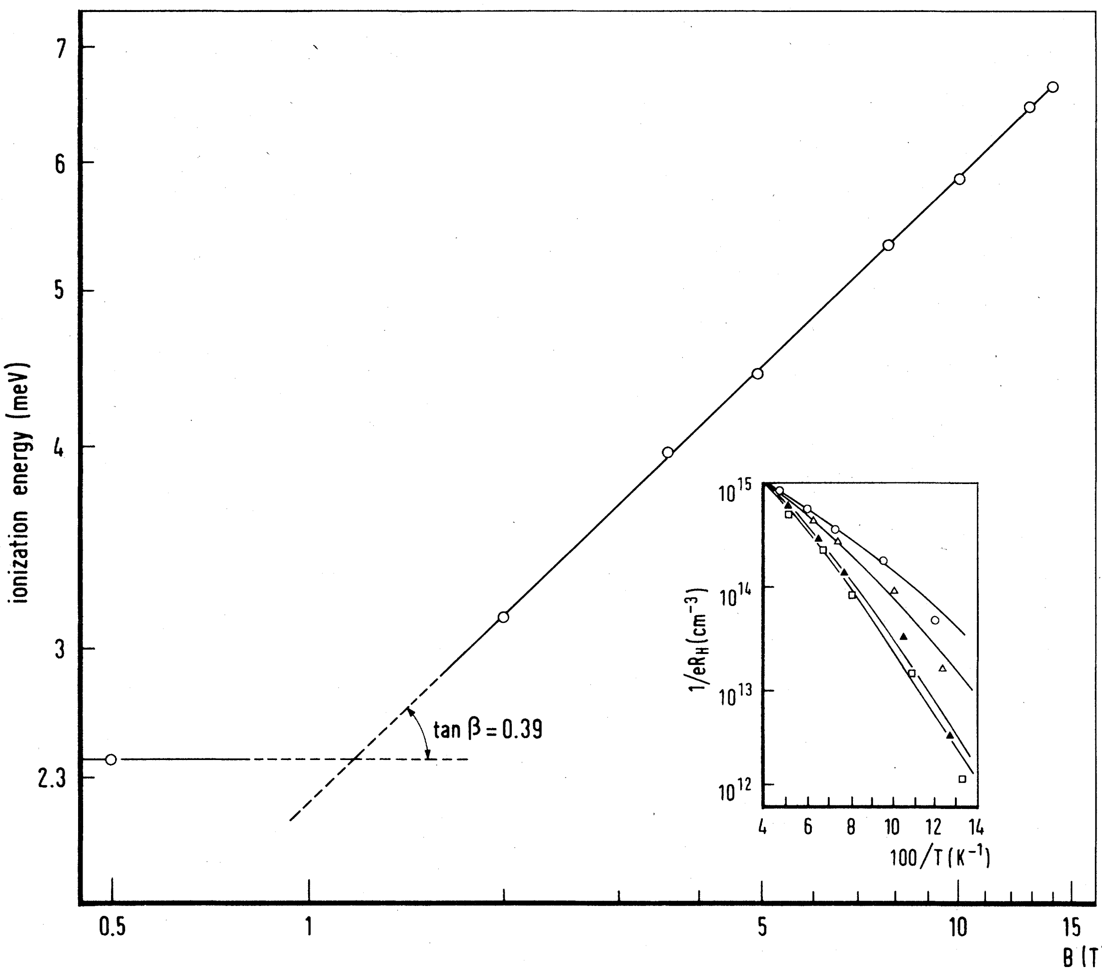

FIG. 3. Magnetic field dependence of the ionization energy derived from the measured temperature dependence of the Hall data (shown in the inset). The drawn lines in the inset show the best theoretical fit for the ionization energy to the data. ○, $B=2.0$ T; △, $B=4.9$ T; ▲, $B=10.0$ T; □, $B=13.9$ T.

Fig. 4(c), this ratio is different from 1 for both the CR and the donor transition. This deviation is attributed to the fact that the constant voltages (V_H and V_I) are determined by the total number of carriers present in the sample, while the change in the voltages (ΔV_H and ΔV_I) results from the absorption which takes place in the irradiated sample area only. For a cloverleaf shaped sample, this irradiated area is only a small part of the total sample area. Complications arising from this problem are circumvented by the comparison with the $1s$-$2p^+$ transition.

These results are quite different from what would be expected from considerations about the energy dependence of the mobility. In the temperature range investigated, scattering from ionized impurities is dominant and therefore the mobility should increase with increasing energy; an increase in the mobility would be expected for the electrons excited to the first Landau level, leading to an increase in the effective mobility. In addition, this effect should become even more important as the Landau-level separation increases. This, in contrast with the experimental findings where no change in the mobility at the higher magnetic fields is found, and a decrease in the mobility at the lower magnetic field is seen. A possible explanation for these observations may be the following: At high magnetic fields, the motion of the electrons is quantized in circular orbits in the plane perpendicular to the magnetic field. The drift velocity parallel to the field direction is unaffected by the magnetic field. The current is in the plane of the circular motion and the direction of the current is determined by the drift velocity of the center coordinate of the cyclotronic motion, not by the cyclotronic motion itself. If the B field is along the z direction and the current in the y direction, the center coordinate depends on the quantum number k_y, which in first order is not

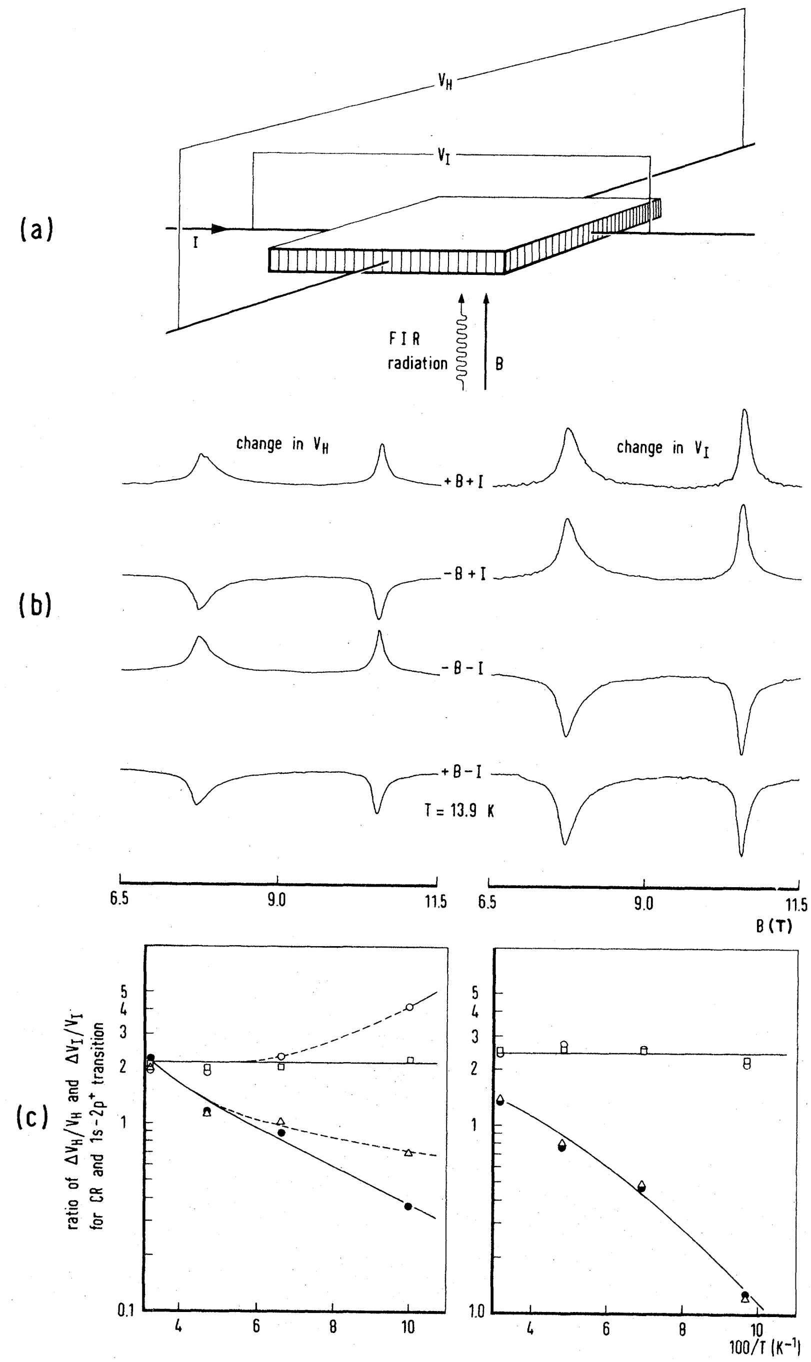

FIG. 4. The configuration for the cyclotron-resonance-induced Hall-effect data (a). (b) shows the measured change in V_I and V_H for $\lambda = 70.6\ \mu m$ as a function of magnetic field for different directions of the current and the magnetic field. (c) shows the ratio of the relative amplitudes $(\Delta V_H/V_H)/(\Delta V_I/V_I)$ for the CR signal (○) and the $1s$–$2p^+$ donor transition signal (□), and the ratios $(\Delta V_H/V_H)_{CR}/(\Delta V_H/V_H)_{1s\text{-}2p^+}$ (△) and $(\Delta V_I/V_I)_{CR}/(\Delta V_I/V_I)_{1s\text{-}2p^+}$ (●) for $\lambda = 118.8\ \mu m$ (left) and $\lambda = 57\ \mu m$ (right).

affected by the magnetic field. This leads to the same mobility for both Landau levels. In lower fields, the mobility is decreased due to increased scattering. Because of the increase in the free-carrier density, there is a corresponding increase in the number of ionized impurities acting as scatterers. In addition, there will also be an increase in the number of acoustic phonons present as the excited carriers will relax to the ground state by multiple phonon emission (see Sec. IV E). However, it is not clear why this latter effect is not observed in the higher magnetic fields.

C. The cyclotron-resonance absorption coefficient

The peak power absorption coefficient for cyclotron-resonance absorption can be derived from a theoretical expression given by Kobayashi and Otsuka[24] and is given by

$$\alpha = C\omega_c\tau(n_0 - n_1)\,. \tag{9}$$

For a direct comparison, $\omega_c\tau$ can be derived from the linewidth at half maximum, and the difference in the occupation densities between the two Landau levels n_0-n_1 can, for low excitation intensities ($n_1 \ll n_0$), be replaced by the thermal equilibrium density n_0^0. The constant C includes the transition matrix element.

The absorption coefficient is derived directly from the transmission data, using $\alpha = [\ln(I'/I'') + (rI''/I')^2 - r^2]/d$, where r is the reflectance at each surface of the sample and I' and I'' are the intensities on and off resonance, respectively. Power fluctuations contribute twice in the determination of α, and apart from that, they also contribute to the experimental uncertainty in $\omega_c\tau$. The absorption coefficient was measured as a function of temperature at three different wavelengths, and the results are plotted against $n_0^0\omega_c\tau$ shown in Fig. 5. The main contribution to the errors in the measurements come from fluctuations in the laser output power.

D. Temperature dependence of CRIC

Figure 6 shows the measured relative change in the conductivity as a function of temperature for the three different wavelengths used in this experiment. The quantity $\Delta\sigma/\sigma$ follows directly from the measured relative change in the voltage $\Delta V_\mathrm{I}/V_\mathrm{I}$ if the sample is biased with a constant current source. The absolute change in conductivity $\Delta\sigma$ is given by

$$\Delta\sigma = -\frac{\mathrm{I}}{V_\mathrm{I}^2}\,\frac{l}{A}\,\Delta V_\mathrm{I}\,.$$

Here, I is the current through the sample, l and A the current length and the cross sectional area. The results for the three different frequencies are shown in Fig. 7 and show a very clear structure, not observable in Fig. 6. The absolute change in conductivity can be derived directly from Eq. (7) and is given by

$$\Delta\sigma = \left[\left(\frac{1}{d}\,\frac{\mathrm{I}_0}{\hbar\omega_c}\,(1 - e^{-\alpha d})t_{0\text{-}1}\,\frac{N_D - N_A - n_0^0}{n_0^0(N_D - N_A)}\right)\frac{\mu_{\mathrm{eff}}}{\mu_0^0} + \frac{\mu_{\mathrm{eff}}}{\mu_0^0} - 1\right] n_0^0 e\mu_0^0(B)\,. \tag{10}$$

This formula reduces to the formula used in Ref.

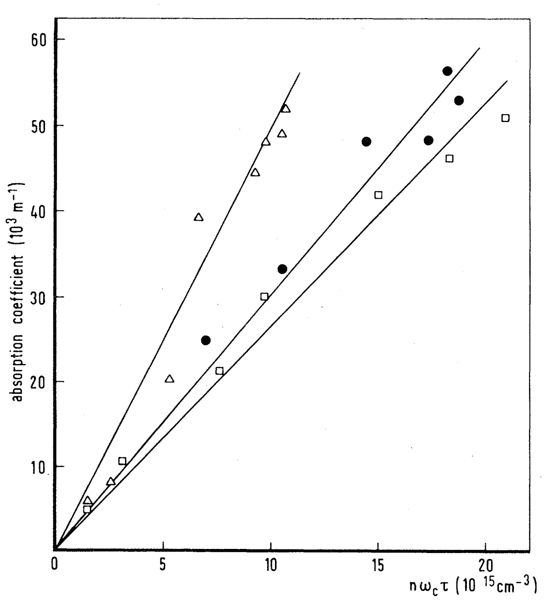

FIG. 5. Measured cyclotron-resonance absorption coefficient as a function of $n_0^0\omega_c\tau$. The drawn line represents the best fit of the linear dependence to the data. △, $\lambda = 118.8\ \mu$m; •, $\lambda = 70.6\ \mu$m; □, $\lambda = 57\ \mu$m.

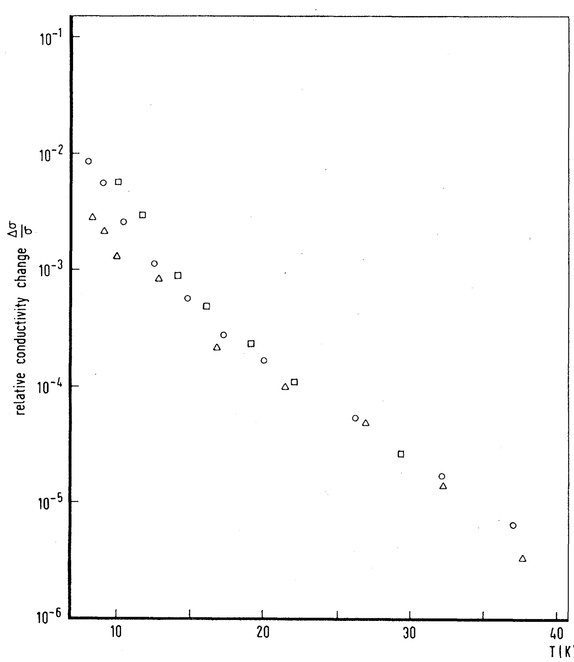

FIG. 6. Measured relative change in the conductivity $\Delta\sigma/\sigma$ at cyclotron-resonance conditions as a function of temperature. △, $\lambda = 118.8\ \mu$m; ○, $\lambda = 70.6\ \mu$m; □, $\lambda = 57\ \mu$m.

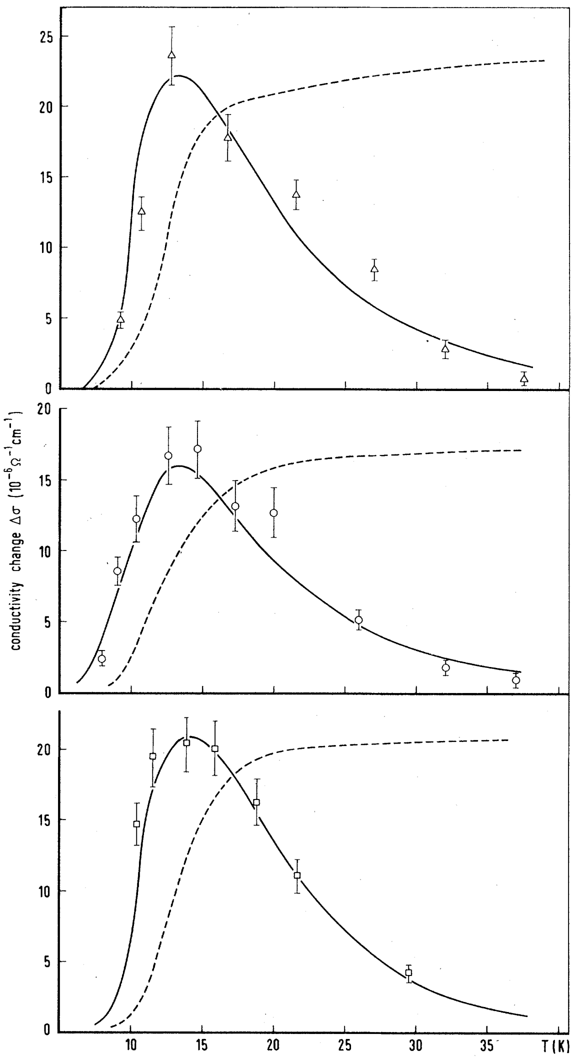

FIG. 7. Measured conductivity change $\Delta\sigma$ at CR conditions as a function of temperature. The dashed curves represent the calculated temperature dependence for a temperature-independent Landau-level lifetime, the solid curves show the calculated conductivity change for a Landau-level lifetime with a temperature dependence of $\propto T^{-3}$. △, $\lambda = 118.8\ \mu$m; ○, $\lambda = 70.6\ \mu$m; □, $\lambda = 57\ \mu$m.

11 if $\mu_{eff}/\mu_0^0 = 1$, and if $\mu_0^0(B)$ and t_{1-0} are assumed to be independent of the temperature. In Ref. 11, a qualitative agreement between measured and calculated CRIC data was obtained by using these assumptions. In a first approximation Eq. (10) can be evaluated with a temperature-independent Landau-level lifetime, but taking into account the temperature dependence of the mobility $\mu_0^0(B)$ at high magnetic fields. The temperature dependence of the mobility at low magnetic fields is shown in Fig. 2; the mobility at higher fields can be derived from $\mu_0^0(B) = a/Rn_0^0 e$, where R is the sample resistance and the constant a is given by the sample geometry. This constant can be calculated from the low-field measurements since both n_0^0 and $\mu_0^0(B=0)$ are determined separately. At high magnetic fields, n_0^0 is determined from Hall measurements and therefore $\mu_0^0(B)$ can be calculated. It is found that the mobility itself is strongly magnetic field dependent, but its temperature dependence remains the same as in the low-field limit (Fig. 2). The dashed line shows the temperature dependence of $\Delta\sigma$ as calculated from Eq. (10) assuming a constant Landau-level lifetime. It can clearly be seen that under these assumptions no agreement between measured and calculated data can be obtained, and therefore the qualitative agreement found in Ref. 11 is rather coincidental It results from the negligence of two temperature dependent factors, i.e., $\mu_0^0(B)$ and t_{1-0}.

The importance of the temperature dependence of t_{1-0} can be seen even more directly in Fig. 6. At low temperatures ($n_0^0 \to 0$) and for a constant mobility ($\mu_{eff}/\mu_0^0 = 1$) Eq. (7) shows that $\Delta\sigma/\sigma$ is directly proportional to t_{1-0}; no temperature-dependent parameters appear in the proportionality constant. The data in Fig. 6 show a strong temperature dependence at low temperatures, once again demonstrating the importance of the temperature dependence of the Landau-level lifetime.

E. Inter- and intra-Landau-level lifetime

The lifetime of the carrier excited to the first Landau level can be determined directly with the help of Eq. (7) from the data shown in Fig. 6. The results are shown in Fig. 8 for the three different frequencies used in this experiment. The uncertainty in the calibration of the absolute power of the radiation leads to an absolute systematic error and within this uncertainty (believed to be of the order of a factor 2), the calculated results show no magnetic field dependence. Therefore the data for $\lambda = 118.8$ and 57 μm were all rescaled by multiplication with a constant factor (< 2) to give the best agreement with the data for $\lambda = 70.6\ \mu$m. The drawn line in Fig. 8 represents a power law of $t_{1-0} \propto T^{-3}$ which gives a fairly good description of the temperature dependence of t_{1-0}. Using this temperature dependence, the conductivity $\Delta\sigma$, as given by Eq. (10), can be calculated and the results are shown in Fig. 7 by the drawn line.

Figure 9 shows the momentum scattering time for scattering within a Landau level, as derived from the linewidth at half maximum for the three different wavelengths and from the dc mobility measurements at $B = 0$. The well-known fact[25] that the scattering time derived from the CR linewidth at low temperatures is longer than that derived from dc transport measurements is clearly illu-

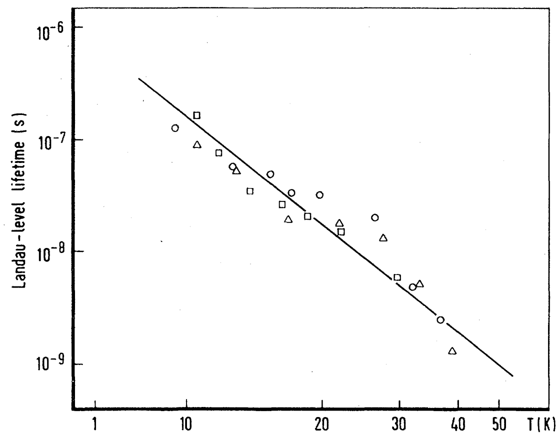

FIG. 8. Landau-level lifetime as calculated from the measured relative change in the conductivity at CR conditions and the measured absorption coefficient. The data for $\lambda = 57\ \mu m$ (□) and for $\lambda = 118.8\ \mu m$ (△) were rescaled to the data for $\lambda = 70.6\ \mu m$ (○) by multiplication with a factor (< 2) to give the best possible agreement. This rescaling factor was within the limits of the uncertainty in the determination of the absolute FIR power. The drawn line represents a temperature dependence of T^{-3}.

strated in Fig. 9. Although the cyclotron-resonance linewidth has been studied actively in the past both theoretically[26-31] and experimentally[32-35] in the temperature region where ionized impurity scattering dominates, the situation is far from being clear. All these models assume that the relaxation time shows an inversely proportional dependence on the density of the ionized impurities, apart from an explicit dependence on the magnetic field and the temperature. In our case,

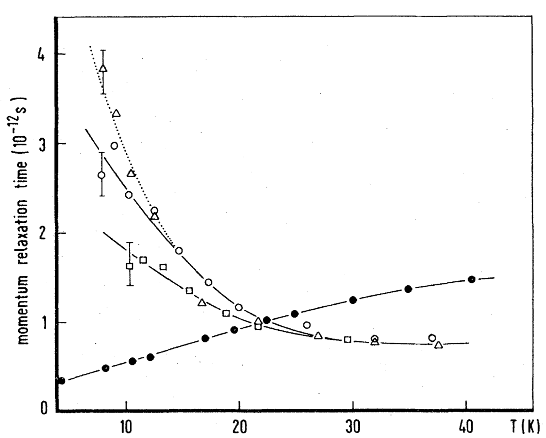

FIG. 9. Momentum relaxation times as a function of temperature derived from the CR linewidth, (△) $\lambda = 118.8$, (○) = 70.6, and (□) 57 μm and derived from the Hall mobility data at $B = 0$ (●). The drawn lines are a guide to the eye.

this density varies strongly with both magnetic field and temperature. The temperature dependence of the linewidth can qualitatively be explained by the temperature dependence of the density of the ionized impurities; this density decreases with decreasing temperature, and consequently the relaxation time increases. However, the observed magnetic field dependence at low temperatures cannot be explained in this way; the density of ionized impurities decreases with increasing magnetic field which leads to an increase of the relaxation time, in contrast with the experimental findings.[36]

The values for the Landau-level lifetimes, as determined from the change in the conductivity $\Delta\sigma/\sigma$ using Eq. (7) (Fig. 8), can be compared with the values of the momentum scattering relaxation time, derived from the linewidth of the CR signal (Fig. 9). The comparison shows that the average time between collisions where only momentum is transferred is 10^{-3} to 10^{-5} times shorter than the average time between interactions where energy is transferred, demonstrating the fact that electron scattering in high magnetic fields is a highly elastic process.

It is of some interest to consider various energy relaxation processes for inter-Landau-level transitions in terms of energy and momentum conservation. A first type of process is a direct vertical optical transition ($\Delta E = \hbar\omega_c$; $\Delta k = 0$). The contribution due to this transition can be estimated from the relaxation rate for spontaneous emission of radiation between Landau levels as given by Gornik *et al.*[37] One gets for the lifetime for spontaneous emission

$$\tau_{sp} = 3cm^*\pi/\eta c^2\mu_0\omega_c^2\,,$$

where c is the speed of light, η the refractive index, and μ_0 the permeability of free space. Using the parameters of the present experimental situation, one gets $\tau_{sp} \simeq 10^{-4}$ s, which is about four orders of magnitude longer than observed in this experiment. A second process is the emission of an optical phonon. The lowest possible energy for an optical phonon in GaAs is 28 meV.[40] For the magnetic field values of the present experiment, the first two Landau levels are always below this energy and therefore it is impossible to have direct optical phonon emission. Gornik *et al.*[38] and Muller *et al.*[39] have shown that for high excitation intensities (number of excited carriers ~10^{13} cm^{-3} and a relaxation time of ~10^{-10} s), electron-electron interaction in the first Landau level can excite an electron to the second Landau level, located above the optical phonon energy. The emission of optical phonons is assumed to be a fast process (10^{-12} s) and the bottleneck is formed by the electron-electron interaction. For low radiation intensities as in the present experiments, the number of excited carriers (10^{10} cm^{-3}) is 2 to 3 orders of magnitude lower and the relaxation time (10^{-8} s) at least 1 order of magnitude longer. Therefore it can be concluded that in the present experimental situation, the electron-electron interaction is too weak to be of significant importance. A third process is the relaxation by direct acoustic phonon emission. Here the conservation laws for energy and momentum form strong restrictions to the possible ways of relaxation; of all possible single phonon emission processes, ranging from a vertical transition ($\Delta E = \hbar\omega_c$; $\Delta k = 0$) to a horizontal transition [$\Delta E = 0$, $\Delta k = \hbar l^{-1}$, $l = (\hbar/eB)^{1/2}$], only those are allowed which match with the phonon dispersion relation.[40] This implies that only a nearly elastic process, with a practically horizontal transition from the first excited to the lowest Landau state, is allowed. Subsequently, the electron loses its energy by relaxing down to the bottom of the lowest Landau level by successive emission of long-wavelength phonons. The temperature dependence of this relaxation path is determined by the probability of the emission of a phonon which is proportional to $(1+N_q)$, where N_q is the density of phonons with momentum q. N_q decreases with decreasing temperature, and therefore this could qualitatively account for the observed temperature dependence of the energy relaxation time.

CONCLUSIONS

A study has been made of cyclotron-resonance-induced conductivity, or cross modulation, in n-GaAs. It has been shown from cyclotron-resonance-induced Hall effect measurements that for high magnetic fields (>8 T) in the temperature region between 8 and 40 K, cross modulation is due to a change in the free-carrier density only, while in lower magnetic fields ($B \approx 6$ T) and at temperatures below 15 K, a decrease in the mobility at cyclotron-resonance conditions is also observed. The increase in the carrier density can be analyzed by the carrier redistribution at cyclotron-resonance conditions, calculated with a simple three-level rate equations model. The temperature dependence of CRIC, calculated from this model, gives a quantitative agreement with the measurements if the temperature dependence of the Landau-level lifetime is taken into account. The discussed mechanism for the change in the free-carrier density under cyclotron-resonance conditions is fairly general and should be present, although not necessarily dominant, in all nondegenerate semiconductors. In this context it should be noted that von Ortenberg[6] has shown that for Te, cyclotron-resonance absorption had no effect on the Hall effect; in that case the change in the mobility must be the major contribution to CRIC. From the absence of an effect on the mobility of the carriers in high magnetic fields it has to be concluded that the usually very well-understood energy dependence of the mobility cannot be used to analyze transport problems under extreme cyclotron-resonance conditions ($\hbar\omega_c > kT$, $\omega_c\tau \gg 1$). From the CRIC data a temperature dependence for the energy relaxation time in the first Landau level $t_{1-0} \propto T^{-3}$ can be deduced; actual energy relaxation times are of the order $t_{1-0} \approx 10^{-8}$ s are found. Within a factor of 2 no magnetic field dependence of this relaxation time is observed. The energy relaxation time combined with the usual momentum relaxation time, as derived from either the dc mobility or the cyclotron-resonance linewidth, show that the ratio of the frequency of collisions with energy transfer only to that where only momentum is transferred decrease from ~10^{-3} at 40 K to ~10^{-5} at 10 K. The energy relaxation path is assumed to be a two step process: first, a quasi-elastic transition from the first to the zeroth Landau level (involving the emission of a low-energy acoustical phonon), followed by a stepwise process of energy relaxation to the bottom of the band with successive emission of long-wavelength phonons.

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