Submillimeter study of the cyclotron-resonance linewidth in CdTe

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The cyclotron-resonance linewidth in n-type CdTe is measured in a broad range of temperature (made possible by the existence of persistent cyclotron resonance), and magnetic field. The width due to scattering on ionized impurities and on acoustic phonons is then calculated numerically with the use of previously published formulas. However, the impurity contribution has been included for all values of k_z, as opposed to the previous reports. Two ways of adding all the contributions are investigated, and the often used Matthiessen-rule approximation is found to be valid in the range of parameters in question. The calculated results are compared also with published data for InSb.

I. INTRODUCTION

The problem of evaluating and understanding the cyclotron-resonance (CR) half-width has quite a long history, with the first papers having been printed in the early sixties. Despite a vast number of papers, both theoretical and experimental, devoted to the problem of CR half-width, a correct interpretation of the obtained data may still be difficult. The most important result is that the cyclotron-resonance linewidth (ΔB) is generated by various scattering mechanisms of the absorbing carriers and should be interpreted as the inverse of the relaxation time (τ) of the electric current:[1]

$$\Delta B/B_{\rm res}=2\tau^{-1}/\omega_c$$

or (since the cyclotron frequency $\omega_c=eB_{\rm res}/m^*$)

$$\Delta B=2(m^*/e)\tau^{-1}\ . \tag{1}$$

Having the CR half-width obtained from experiment, one can easily obtain from Eq. (1) an important parameter describing the material, namely the mobility. Of course, since the sample is subjected to a static magnetic field (sometimes large), the mobility thus obtained may not necessarily be equal to the static mobility, yet the cyclotron-resonance data offer a convenient (no contacts) and reliable criterion of the quality of the sample.

In the present work we report a systematic study of the width in CdTe, which is superior to Ge and InSb (simple, spherical, parabolic conduction band with a relatively large effective mass) and GaAs (only recently have purer samples become available). A very unique property of the CdTe used in our measurements, namely persistent cyclotron resonance[2] (free electrons are present or "persist" even below 4.2 K), allowed us to extend considerably the range of temperatures used. In addition, high mobility of the samples permits measurements at very low magnetic fields. Using a theoretical model for ionized impurity and acoustic phonon scatterings we were not only able to reasonably fit the data with virtually no adjustable parameters, but detailed calculations also enabled us to test the so-called "Matthiessen rule," used when one has to take into account more than one scattering mechanism. We have excluded polar optical scattering from our analysis, since as shown in transport measurements[3] its magnitude in CdTe for $T<30$ K is more than 1 order of magnitude below the acoustic contribution, and we assume that this is also true for cyclotron-resonance scattering. On the other hand, contrary to the analysis of the CR width in other semiconductors (see a review by Otsuka[4]) we did not consider the influence of neutral impurities; our results, however, do not completely exclude this possibility.

The theoretical description of the CR half-width is based on the calculation of the complex conductivity tensor $\sigma(\omega)$ (in the presence of a magnetic field) for $\omega\approx\omega_c$. The power absorption for a circularly polarized electric field of frequency ω is proportional to the real part of the tensor: $P\sim{\rm Re}[\sigma(\omega)]$. Once the absorption $P(\omega)$ is determined, the cyclotron-resonance width is obtained according to the equation:

$$\Delta B=(m^*/e)(\gamma_R+\gamma_L)\ , \tag{2}$$

where γ_R and γ_L are defined by

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$$P(\omega_{\max}+\gamma_R)=\tfrac{1}{2}P(\omega_{\max}) ,$$

$$P(\omega_{\max}-\gamma_L)=\tfrac{1}{2}P(\omega_{\max})$$

and $\omega_{\max}$ corresponds to the maximum power absorption (usually $\omega_{\max}=\omega_c$, however, for broad lines, $\omega_{\max}>\omega_c$). The fundamental problem now is to find the quantum mechanical formula for the the dynamic magnetoconductivity tensor $\sigma(\omega)$ near the resonance. Assuming low electron concentration and a nondegenerate semiconductor (hence Boltzmann distribution) the result for the power absorption is[5]

$$P(\omega)=\{4e^2n_e\hbar/[2(m^*)^3T]^{1/2}\}\times\int_0^\infty dk_z \exp(-\hbar^2k_z^2/2m^*kT)\times\{\Gamma(k_z)/[(\omega-\omega_c)^2+\Gamma^2(k_z)]\} , \quad (3)$$

where n_e is the electron concentration and $\Gamma(k_z)$ is the function describing the scattering. A more detailed discussion of the exact form of $\Gamma(k_z)$ will be given below. One can see from Eq. (3) that if Γ were independent of k_z, the integral could easily be evaluated and the line would be perfectly Lorentzian; From (2) one would then obtain

$$\Delta B=2(m^*/e)\Gamma , \quad (4)$$

where $\Gamma=\gamma_R=\gamma_L$.

Equation (4) if formally equivalent to Eq. (1) provided $\Gamma=\tau^{-1}$ and for that reason Γ^{-1} is often called a "relaxation time," a rather unsuitable term for a function. The relation between ΔB and $\Gamma(k_z)$ is usually not given by a simple formula like Eq. (4), and a determination of the CR half-width once the function $\Gamma(k_z)$ is known is not straightforward; and certainly it is incorrect to associate the width with $\Gamma(0)$, as is sometimes done [a much better approximation is obtained by evaluating Γ for $k_z=(2m^*kT)^{1/2}/\hbar$]. For the width of the resonance we will use throughout this article the correct formula (2) and all corresponding widths will be given in s^{-1}, i.e., in the units of Γ; to get the width expressed in T one has to multiply the result by $2m^*/e$.

II. CYCLOTRON-RESONANCE HALF-WIDTH

A. Ionized impurity scattering

This is the major contributor to the width and many theoretical calculations with different formalisms employed are available. The results are often contradictory, e.g., there are approaches where the width is an increasing or, conversely, decreasing function of the temperature. A good illustration of what has been done are Figs. 5–7 presented by Van Royen *et al.*,[6] where the results of most of the past theoretical works are displayed against the experimental data (for InSb) obtained by Matsuda and Otsuka.[7] Since the theoretical results are usually valid in a certain (sometimes narrow) range of concentration or temperature, one has to be rather careful in selecting appropriate theories (and preparing figures like those of Van Royen's); nevertheless it gives a good flavor of the serious difficulties one can encounter when trying to compare measured CR width with a theory.

In earlier works dealing with the problem of evaluating the conductivity tensor $\sigma(\omega)$, which was necessary in order to obtain the final expression for CR width, an artificial division into nonadiabatic and adiabatic processes used to be popular. In that terminology nonadiabatic scattering arises when a collision between an electron and a scatterer causes the electron to change its momentum, which is accomplished by a redistribution of its total energy among its internal states. It was first shown by Kawabata[1] that the CR width resulting form such a process is described by the formula (SI units);

$$\Gamma=(2\pi/\hbar^2)(e^2/4\pi\epsilon_0\kappa)^2(N_i/\omega_c k_z) , \quad (5)$$

where N_i and κ are the concentration of ionized impurities and the static dielectric constant of the host crystal, and k_z the momentum along the magnetic field. Setting $k_z=(2m^*kT)^{1/2}/\hbar$, as is often done, we arrive at a formula predicting a $B^{-1}T^{-1/2}$ dependence.

The adiabatic process (Kawamura *et al.*,[8] Miyake[9]) is based on the observation than an electron, when subjected to an electric field (provided by ionized impurities) changes its cyclotron frequency by

$$\Delta\omega_c=(1/2m^*\omega_c)(V_{xx}+V_{yy}) ,$$

where V_{xx} and V_{yy} are the second derivatives of the potential energy at the center of the cyclotron orbit, which lies in the $x-y$ plane, the magnetic field being along the z axis. The broadening is considered to be the result of the superposition of the randomly shifted lines and is proportional to the square root of impurity concentration ($\sim B^{-1/4}N_i^{1/2}$). Proportionality to $N_i^{1/2}$ reflects the behavior of the average electric field in the crystal rather then the "real" scattering which should be (and is, as will be seen below) proportional to N_i. In this context it is interesting to note that quite often in the past[10,11] the adiabatic process was associated with the observed increase of the CR linewidth in the high-field region, where "... the electron is able to complete its cyclotron motion within the force range of the impurity," and where nonadiabatic scattering is really negligible. We believe that these interpretations are not correct, and the effect is due to the interaction with acoustic phonons.

Restricting ourselves to the ultraquantum light, i.e., considering only cyclotron-resonance transitions between the Landau levels $N=0$ and $N=1$ (or assuming $\hbar\omega_c \gg kT$), the following formula holds:[5]

$$\Gamma(k_z)=(2\pi)^3N_i\int d^3q\,|V(q)|^2t^2e^{-t}\times\{\Gamma(q_z)/[E(k_z)-E(k_z-q_z)]^2+\hbar^2\Gamma^2(q_z)\} , \quad (6)$$

where $V(q)$ is the Fourier transform of the scattering potential, $t=\frac{1}{2}r_0^2$, $r_0=(\hbar/eB)^{1/2}$ and $E(k_z)$ is the electron energy [$E(k_z)=\hbar^2k_z^2/2m^*$ for a parabolic case].

The scattering potential seen by a moving electron may be approximated by a screened Coulomb potential:

$$V(r)=(e^2/4\pi\epsilon_0\kappa r)\exp(-r/\lambda) ,$$

where λ is the force range of the impurity potential. The Fourier transform of the above potential is introduced into Eq. (6), and the final expression for the width is obtained:[12]

$$\Gamma(k_z)=(4r_0^2N_i/\hbar^2)(e^2/4\pi\epsilon_0\kappa)^2\int_0^\infty dt\, t^2e^{-t}\int_{-\infty}^{\infty}dq_z[1/(q_z^2r_0^2+2t)^2]\Gamma(q_z)/[\hbar^2q_z^2(2k_z-q_z)^2/4(m^*)^2+\Gamma^2(q_z)] . \quad (7)$$

Two approximations are included in the above equation: The potential is assumed to be purely Coulombic, i.e., $\lambda^{-1}=0$ and the energy band for the electron is parabolic. Screening, which is a must in a dc case, is not necessary here (formula 7 is not divergent for an unscreened potential), and since the measurements are performed in very pure samples in the microwave or far-infrared (FIR) spectral region, the nonparabolicity can also be ignored. This is apparently not the case for InSb.

The formula (7) when solved approximately yields results corresponding either to the nonadiabatic scattering, namely for low-impurity concentration, or to the adiabatic scattering in the large-impurity-concentration regime and/or low temperature.

There exists in the literature an attempt to solve Eq. (8) numerically for the case of Ge (Ref. 13) and for intermediate values of k_z, but the results are not presented clearly.

We have succeeded in obtaining fairly accurate numerical solutions of Eq. (7) for several materials. To become better acquainted with the properties of the solutions we illustrate the results for a particular case of the cyclotron-resonance width in CdTe with the following numerical values: $m^*=0.1m_e$, and $\kappa=9.6$. The results for other semiconductors are generally similar.

The major feature of the calculated cyclotron-resonance linewidth is its inverse proportionality to B and T over almost the entire range of the relevant magnetic field and temperature (Figs. 1 and 2). The tendency of the width to saturate at low temperature and/or low magnetic field is barely seen, since in that region $\Delta B\sim B_{\rm res}$ and the observability of the cyclotron-resonance line is reduced. A similar feature can be seen in Fig. 3, showing the CR width versus concentration of ionized impurities. The dependence loses its starting (for low concentration) simple linear behavior tending toward being proportional to $(N_i)^{1/2}$, again, however, reaching a region where $\Delta B > B_{\rm res}$ very soon. A general conclusion is that "adiabatic" scattering, although present in the scattering by ionized impurities, cannot be observed alone in real experiments, where the "nonadiabatic" type always dominates.

B. Acoustic phonon scattering

The perturbing potential energy resulting from electron-phonon interaction is taken in a usual form:

$$U=\sum_{\mathbf{q}}(\beta_{\mathbf{q}}b_{\mathbf{q}}+\beta_{\mathbf{q}}^{\dagger}b_{\mathbf{q}}^{\dagger}) ,$$

where $b_{\mathbf{q}}$ and $b_{\mathbf{q}}^{\dagger}$ are annihilation and creation operators of a phonon with momentum $\mathbf{q}$ and $\beta_{\mathbf{q}}$ is the interaction operator usually taken in the form $B_{\mathbf{q}}=C_{\mathbf{q}}\exp(i\mathbf{qr})$, where $C_{\mathbf{q}}$ is a constant which depends on the type of phonon. For the interaction via a deformation potential,

$$C_{\mathbf{q}}=iD(\hbar q/2\rho S_0)^{1/2} .$$

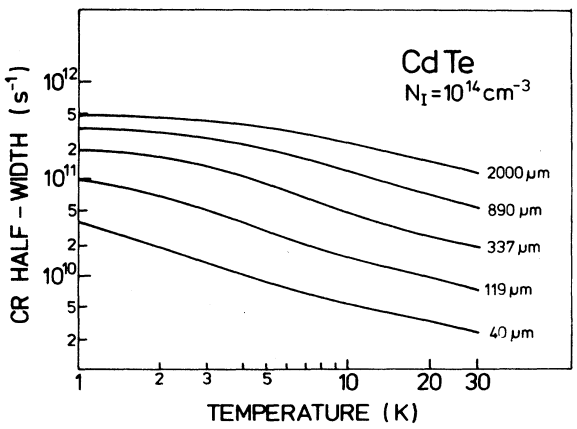

FIG. 1. Cyclotron-resonance half-width in CdTe due to scattering on ionized impurities only, as a function of temperature for selected wavelengths between 40 and 2000 μm. The concentration of ionized impurities is as indicated.

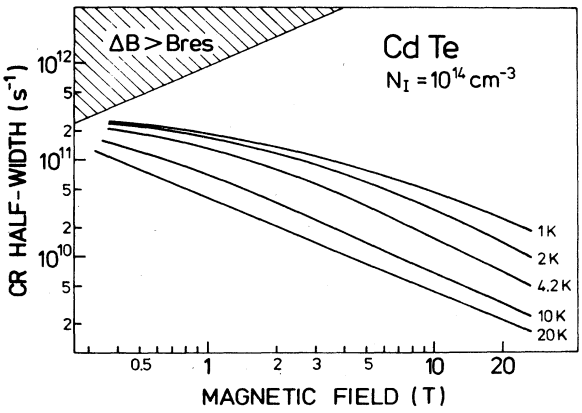

FIG. 2. Cyclotron-resonance half-width in CdTe due to scattering on ionized impurities only, as a function of the magnetic field for several temperatures. There is a lack of inverse proportionality for low magnetic fields. The shaded area represents the region where the condition $\omega_c\tau>1$ is not satisfied, and the absorption line cannot be observed.

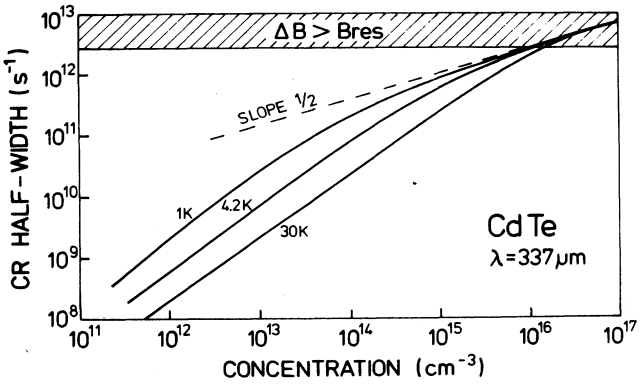

FIG. 3. Cyclotron-resonance half-width in CdTe due to scattering on ionized impurities only, as a function of the concentration of ionized impurities. The dependence is linear for small concentrations and gradually becomes proportional to the square root of the concentration. The square-root dependence can be observed for low temperature only; at higher temperatures the condition $\omega_c\tau<1$ occurs for relatively small concentrations, and the cyclotron-resonance half-width cannot be measured.

Here, D is the deformation potential, ρ the mass density, and S_0 the sound speed. The interaction via a piezoelectric coupling in cubic crystals is described by[14,15]

$$C_q=eP\langle K(\theta)\rangle(\hbar/2\rho S_0 q)^{1/2}/\epsilon_0\kappa ,$$

where $\langle K(\theta)\rangle$ is a factor reflecting the anisotropy of the interaction, averaged over directions, and P is the only nonvanishing component of the piezoelectric tensor.

The problem of evaluating the dynamic conductivity in the presence of this type of scattering has been also extensively studied in the past, usually with the use of the same formalisms as in the case of ionized impurities.[1,16–20]

However, the authors often considered only the elastic type of scattering[1,16,18] which under certain experimental conditions leads to incorrect results. We have used the results given by Srinivas *et al.*[19] which are valid for an arbitrary degree of inelasticity. The appropriate function Γ_{ph} is a sum of the contribution due to emission and absorption processes:

$$\begin{aligned}\Gamma_{ph}(k_z)&=\Gamma_{em}+\Gamma_{ab} ,\\ \Gamma_{em}&=2\pi\int d^3q[1+N(q)]|C_q|^2 t^2 e^{-t}\\ &\quad\times\Gamma/\{[E(k_z-q_z)-E(k_z)\\ &\quad+\hbar\omega_q]^2+\hbar^2\Gamma^2\} ,\\ \Gamma_{ab}&=2\pi\int d^3q\, N(q)|C_q|^2 t^2 e^{-t}\\ &\quad\times\Gamma/\{[E(k_z-q_z)-E(k_z)\\ &\quad-\hbar\omega_q]^2+\hbar^2\Gamma^2\} ,\end{aligned} \tag{8}$$

where $t=\frac{1}{2}r_0^2(q_x^2+q_y^2)$ and $N(q)$ is the phonon occupation number

$$\begin{aligned}N(q)&=[\exp(\hbar\omega_q/kT)-1]^{-1}\\ &\approx[\exp(\hbar S_0 q/kT)-1]^{-1} .\end{aligned}$$

The similarity between equations describing the impurity and phonon interactions is obvious, and of course, the same way of obtaining the solutions can be followed.

For illustration, we plot the calculated CR half-width for the case of germanium, where the deformation potential is known quite precisely,[16] and where for the purest samples available one can expect the impurity contribution to be reduced to an undetectable limit. Figures 4 and 5 present the CR width versus temperature and magnetic field, provided only acoustic phonon scattering is effective (i.e., $N_i=0$). These dependences are more complicated than previously calculated, due to the fact that, e.g., the T dependence is already contained from the start in the equation for Γ_{ph} (via phonon occupation numbers) as opposed to the case of ionized impurities, where the T dependence comes from the averaging procedure only [see Eq. (3)]. The width generated by the piezoacoustic coupling (calculated for CdTe) shows essentially identical behavior, with the absolute values either comparable to (for $B<1T$) or much smaller than (for $B>1T$) those given by deformation potential scattering.[22]

C. Electron-electron scattering

A misunderstanding of the effect of electron-electron scattering on the CR width exists in the literature. A tempting idea that this type of scattering can be described analogously to the ionized impurity scattering is not correct, and consequently no formula derived for the impurity case can be used for electron-electron scattering. This type of scattering differs qualitatively from all the other modes of scattering, since (1) the interaction considered is "internal" and therefore incapable of changing the current in the first order, and (2) the e-e collisions are clearly inelastic and the relaxation time concept is, strictly speaking, not valid in this case. There are papers, however, both theoretical and experimental, deal-

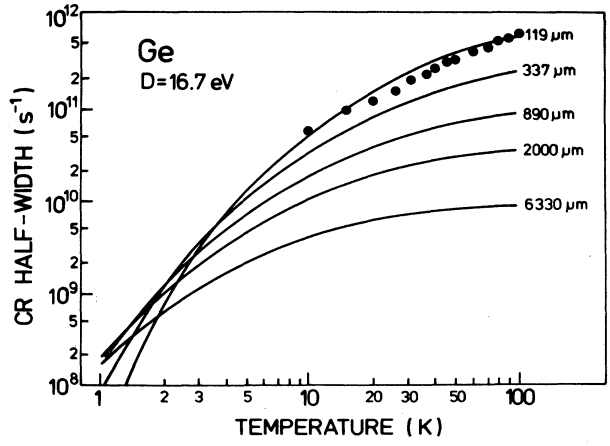

FIG. 4. Cyclotron-resonance ([111] direction) half-width in Ge due to scattering on acoustic phonons only, as a function of temperature. As expected, the width is strongly dependent on temperature. Experimental results (Ref. 21) are shown for comparison. The curves were not fitted to the results, the deformation potential is taken from Ref. 16.

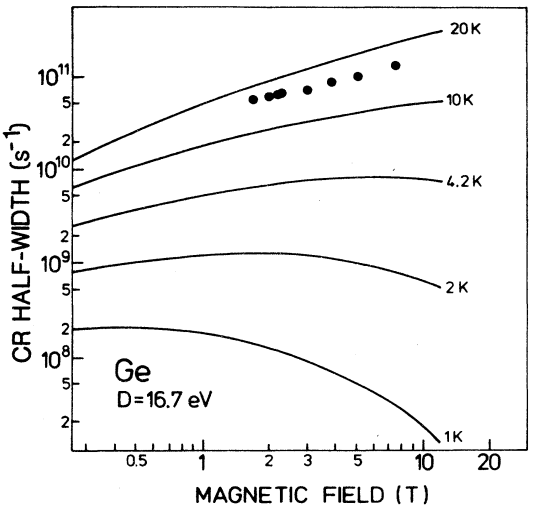

FIG. 5. Cyclotron-resonance ([111] direction) half-width in Ge due to scattering on acoustic phonons only, as a function of the magnetic field. The decrease observed for low temperatures is due to the inelasticity of the scattering. Experimental results (Ref. 21) (not fitted) are shown for comparison.

ing with the problem in the dc case (see a review by Zawadzki[14]). It has been shown that under certain conditions (nondegenerate electron gas in InSb) one can expect the dc mobility to be reduced by as much as 40% of its initial (i.e., without e-e interaction) value; furthermore, it is an increasing function of electron concentration (the influence of the e-e interaction vanishes for a degenerate electron gas). Unfortunately, to our knowledge, no theoretical undertakings concerning the influence of e-e interactions on CR half-width exist. There were, however, some experimental attempts to establish whether this type of interaction can change the width of the resonance,[23,24] and the conclusions were that the effect of e-e interactions can barely be seen. Especially the CR width measured on samples where persistent cyclotron resonance was present and the carrier concentration can easily be regulated, suggest that the e-e interaction can account for not more than a few percent increase of the resonance width, substantially less than in the mobility reduction in a dc case. In the following analysis of the experimental data we will, therefore, neglect this interaction.

D. CR width in the presence of several mechanisms

In practice it it almost never possible to limit considerations to a single scattering mechanism. It is generally accepted that for various scattering modes (except the "internal" ones, due to electron-electron interaction) the transition probabilities are additive. In this case the so called "Matthiessen rule" holds:

$$\Gamma(k_z)=\sum_n \Gamma_n(k_z)\ . \tag{9}$$

The above relation does not imply that one can add the average widths associated with the various mechanisms in order to calculate the total width. Instead, the above sum is introduced into Eq. (3), and the resulting total width is obtained.

Recently Srinivas *et al.*[19] have questioned the applicability of the Matthiessen rule. They have shown that Eq. (9) is valid only if all the scattering modes have a linear dependence on the concentration of scatterers. Their proof, however, is not convincing, for it is derived only for the case when one kind of scatterer is present (e.g. ionized impurities). Since the phonon contribution does not depend on the concentration of impurities and forms a completely independent interaction mechanism, there are no physical arguments to exclude the Matthiessen rule represented by Eq. (9). However, to perform the summation of all the mechanisms correctly one should start the calculation of the dynamic magnetoconductivity assuming from the beginning the existence of all the scattering agents. This procedure has in fact been outlined in Srinivas's paper;[19] however, no numerical calculations were given. We have checked that the difference between a rigorous treatment and the Matthiessen rule is small, and the relevant numerical results will be give in a subsequent paper. For the purpose of this work the Matthiessen rule [Eq. (9)] will consequently be used.

III. COMPARISON WITH EXPERIMENTAL DATA

A. CdTe

Cadmium telluride offers many advantages over other semiconductors in the study of the cyclotron-resonance linewidth. First, its nonparabolicity due to the interaction of valence and conduction bands (via $\mathbf{k}\cdot\mathbf{p}$ terms) is negligible, and if one is performing experiments for $\hbar\omega < 10$ meV the other "nonparabolicity," due to the polaron coupling, is also small. The conduction band is spherical, and the shallow impurity transitions (if present) are shifted away from cylotron resonance. The situation fits ideally the assumption of nearly all theoretical models, and the availability of extremely high-quality crystals also facilitates the experiment. Surprisingly, relatively few papers concerning the CR half-width in CdTe exist. Our first results[3,25,26] suggested, however, that CdTe is an ideal material for the study.

The samples were grown in a vertical Bridgeman furnace and then zone refined. The concentration of electrically active donors and acceptors was below 10^{14} cm^{-3} with the compensation ratio (N_d/N_a, where N_d and N_a are the concentrations of donors and acceptors, respectively) between 2 and 4. The samples displayed persistent cyclotron resonance, but its presence did not affect the observed width of the resonance.[26] All the measurements were performed using nonpolarized light from an optically pumped far-infrared laser operating on several wavelengths longer than 100 μm; the magnetic field was provided by a pulsed magnet capable of giving 35 T. A fast helium-cooled Ge photoconductor was used as a detector, as well as an InSb Putley detector for longer wavelengths. A flowing-gas-type cryostat, equipped with a calibrated-Si diode was used to change and control the temperature of the sample in the range 4.2–70 K with an accuracy of 0.5–5 K, depending on the temperature. The

results were recorded and analyzed on a computerized data-acquisition system.

In a pulsed-type experiment data can be recorded while sweeping the magnetic field either up or down. A typical example of resulting curves, presented on Fig. 6, shows virtually no lag of the recovered signal (although the sweep down takes roughly an order of magnitude longer than the sweep up); therefore, the shape of the line is not distorted by any time constant introduced by the detector or electronics. We used, however, only the data from the sweep down.

In order to extract from the measured curves the real width of the resonance it has been supposed that sample transmission obeys the law: $T=T_0\exp(-ad)$, where T_0 is the transmission far from the resonance, a is the absorption coefficient, and d the sample thickness, i.e., multiple reflections are not considered. Hence the transmission at half-absorption is given by

$$T_{1/2}=(T_0T)^{1/2},$$

where T is the sample transmission at the resonance field. The results presented below are obtained by measuring the CR width at $T_{1/2}$. The main error is thus introduced by the use of nonpolarized radiation. We have assumed an equal partition of the polarization into cyclotron-resonance–active (CRA) and–inactive (CRI) modes.

In the following discussion of the experimental results two points should be observed. First, increasing the temperature in the region $T<30$ K usually ionizes neutral donors (there are some N_d-N_a neutral donors at low temperature) and the total concentration of ionized impurities is increased to N_d+N_a. The total concentration of impurities was assumed to follow the formula

$$N_i=2N_a+[N_c/2][(N_d-N_a)/N_a)]\exp(E_d/kT),$$

up to N_d+N_a, where E_d is the shallow-donor ionization energy and N_c is the conduction-band effective density of states. We have assumed $N_d=2N_a$, a condition typical for measured samples.

Second, increasing the magnetic field causes freezing out of the carriers onto donors, and consequently the concentration of ionized impurities is changed. We did not, however, take this effect into consideration.

The temperature dependence of the CR linewidth is shown in Fig. 6 for all the used wavelengths (890–119 μm). The results are obtained on three different but essentially equivalent CdTe samples, and it is not necessary to distinguish the points obtained on each sample. A general feature of the CR half-width shown is its monotonic dependence on the temperature, suggesting that the scattering on acoustic phonons is dominant. On the other hand, the influence of impurities cannot be neglected, otherwise the clearly nonmonotonic dependence on magnetic field (with a minimum), shown in Fig. 7, cannot be understood. It is interesting that the minimum has been observed even for 70 K, and occurred for all temperatures at nearly the same magnetic field (around 3 T).

All of the above-mentioned mechanisms, namely scattering on ionized impurities and on acoustic phonons (through both deformation potential and piezoelectric coupling) are thus included in the comparison of the measured CR width and the theoretical predictions. An effort has been made to keep the concentration of the impurities as close as possible to those given by independent Hall measurements ($N_d=5.7\times10^{13}$ cm^{-3}, $N_a=1.9\times10^{13}$ cm^{-3}) allowing, however, for its small change to improve the agreement. The other material parameters are as follows: $m^*=0.1m_e$, $\kappa=9.6$, $\rho=5855$ kg/m^3, $S_0=3110$ m/s, $f=6.4\times10^{-5}$, where f is a dimensionless parameter describing the piezoelectric coupling in an isotropic model.[15] The deformation potential constant D was thus the only adjustable parameter.

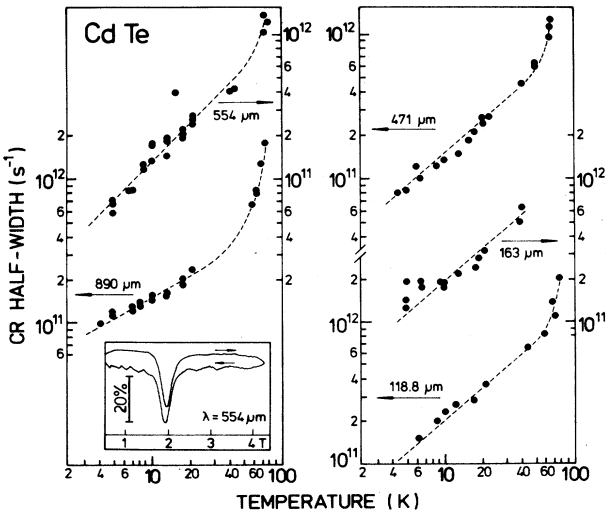

FIG. 6. Results of cyclotron-resonance half-width measurements for CdTe plotted against temperature. Inset show measured transmission for both field-up and -down sweeps with indication of a percent transmission scale obtained for $\lambda=554$ μm and $T=20$ K.

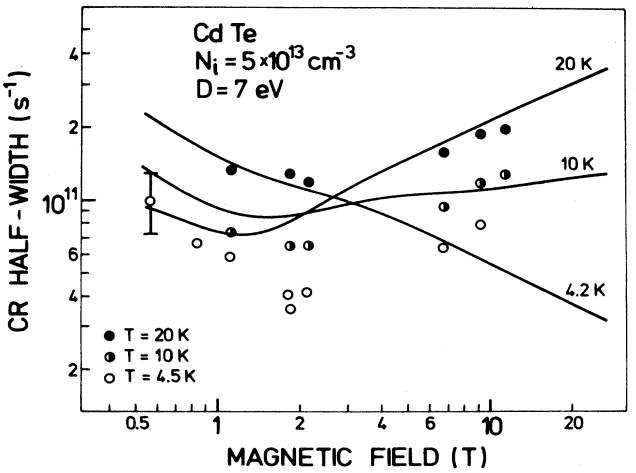

FIG. 7. Results of cyclotron-resonance half-width measurements for CdTe plotted against the magnetic field (closed circles); lines show calculated results for $T=4.2$, 10, and 20 K. The typical error is indicated on the first far-left experimental point.

Figures 7 and 8 present the fit obtained by setting $D=7$ eV and $N_i=5\times10^{13}$ cm^{-3}, a value very close indeed to the Hall measurement assessments. Since all the measurements were performed well below the LO phonon energy (170 cm^{-1}), the influence of "pinning" on the width was neglected, although the position of the resonance was modified. A detailed discussion of the polaron nonparabolicity in CdTe is given elsewhere.[27] The effect of the piezoelectric coupling was found to be visible, although small enough not to influence the overall behavior of the CR width; consequently, the parameter f was not changed. The value of the deformation potential cannot be changed much, since the high-field end of the curves is very sensitive to D. From our results we assigned a value of $D=7\pm2$ eV to the deformation potential in CdTe. This value has to be compared with other published estimates for the deformation potential in CdTe, which cover a range of 2.5–10 eV. Our result apparently supports the higher-value reports, but the deformation potential in CdTe is still considerably smaller than, e.g., in Ge or InSb. The inability of a correct qualitative description of ionized impurity scattering is clearly visible. The neglect of the freezing out of electrons and the subsequent change of impurity concentration can be partly responsible for the imperfect fit, especially at low temperatures (4.2 K). As will be seen below, the fit for InSb, where such freezing is less important, is better despite the inherent inadequacy of using InSb with the parabolic model.

However, the main problem lies in the evidently incorrect description of the interaction with phonons for low temperature and high magnetic field, where the field dependence predicted by the theory completely rules out any possibility of reproducing a minimum, clearly visible on the experimental data. On the other hand, the phonon model works well for higher temperatures. The experimental points[21] indicated on Figs. 4 and 5 coincide satisfactorily with the theory (there are no fitting parameters). One can thus derive a general conclusion, that the theory[19] describing the acoustic phonon scattering must be revised and corrected.

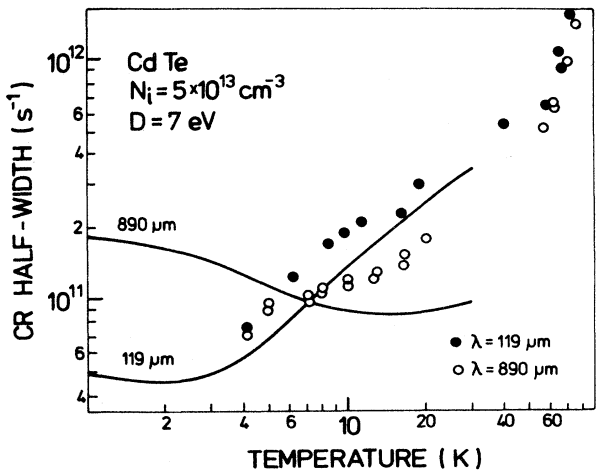

FIG. 8. Results of cyclotron-resonance half-width measurements for CdTe plotted against temperatures (closed circles); lines show calculated results for the same sample parameters.

B. InSb

Although not well suited for the cyclotron-resonance study of the scattering mechanisms, the material was very popular in that respect for several years and there exists in the literature quite a lot of experimental data. The main drawback of InSb is its small effective mass, and consequently rather large nonparabolicity. This means that the cyclotron transitions from different low-lying electron levels do not have the same resonant fields, and the line is asymmetrically broadened even at 4.2 K, where as much as 99% of the free-electron population occupy the lowest spin-up Landau level unless very pure samples and/or high magnetic fields are used. The other disadvantageous factor is the k_z-dependent denominator in the expression for absorption (and Γ), also producing the tail on the high-magnetic-field side of the cyclotron resonance. Therefore one has to rely on a model of the energy bands in InSb in order to "extract" the real width (to be compared with the Γ functions described earlier) from the experimental data. That inevitably introduces a systematic error, difficult to estimate. The popular three-band model is often used in that context. Also, the near-lying impurity transition disturbs the CR line, and the data for $B<0.5$ T and $B>0.1$ T are scarce and unreliable. InSb, however, possesses a property of great advantage. Within the temperature range 4 K$<$T$<$50 K the concentration of ionized impurities can be regarded as almost constant (all donors are ionized), and freezing out can be neglected, which somewhat simplifies the interpretation.

Although the theoretical model presented in this paper was developed for parabolic semiconductors and therefore does not really apply well to InSb, a comparison with existing experimental data is of interest. In our calculations, both contributions to the CR half-width (acoustic phonons through deformation potential only) were added according to Eq. (9). We made a gesture towards including nonparabolicity by making the effective mass dependent on the energy of the CR transition being, however, fully aware of the need for using correct wave functions in an appropriate nonparabolic model.

The deformation potential D was the only adjustable parameter. All other material constants were taken from the literature: $m^*=0.0139m_e$, $\kappa=17.6$, $\rho=5780$ kg/m^3, $S_0=3775$ m/s.

Figure 9 is an example of the obtained fit for the experimental data presented by McCombe *et al.*[23] (sample no. 1), where the width as a function of magnetic field for an unspecified temperature has been shown. The value of the deformation potential is $D=15$ eV (well below the estimate of 60 eV given by Dunn and Suzuki[17]), and we have to use a value of the impurity concentration $N_i=1.5\times10^{14}$ cm^{-3}, while the authors claimed that there are some 3×10^{14} cm^{-3} charged impurities in the sample. The minimum has been reproduced for a slightly higher magnetic field, however without knowing the temperature further discussion is impossible, especially in the framework of the parabolic model.

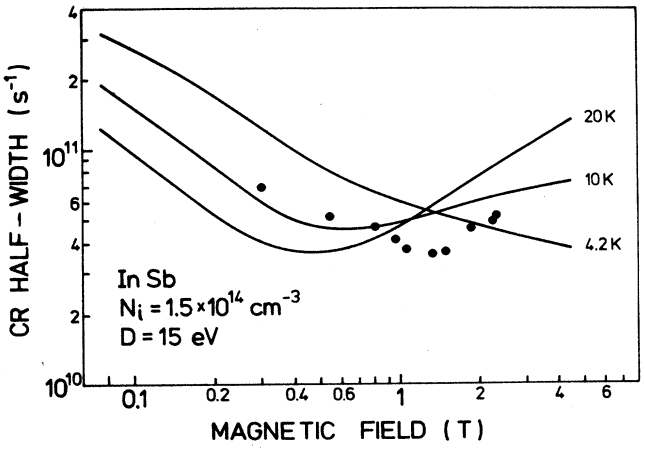

FIG. 9. Results of cyclotron-resonance half-width measurements for InSb taken from McCombe *et al.* (Ref. 23) (for an unspecified temperature); lines show calculated results. The concentration of impurities differs from that given by the authors by a factor of 2.

Generally we feel that the agreement is reasonable and cannot be expected to be better considering the crudeness of our approach to the case of InSb.

IV. SUMMARY

We have measured cyclotron resonance in pure *n*-CdTe in a very broad range of temperatures (up to 80 K) and magnetic fields (up to 11 T). Such measurements were possible due to the exceptional high quality of the CdTe crystals displaying persistent cyclotron resonance. The theoretical description of the width of the resonance was based on previously published approaches; however, the equation given by Fujita and Lodder[12] for ionized impurity scattering was solved numerically for *all* values of k_z, as opposed to the previous reports where only limiting values of k_z (either very low or very high) were considered. All the contributions (ionized impurities and acoustic phonons via deformation potential and piezoelectric coupling) were added according to the Matthiessen rule; the other method of summing the individual contributions, proposed by Srinivas *et al.*,[19] yielded essentially identical results. Since scattering on optical phonons was not included in our calculations, only the data for $T \leq 30$ K were fitted, and a value of the deformation potential in CdTe $D = 7 \pm 2$ eV was obtained. Although we have used probably the most complete theoretical descriptions of the scattering on ionized impurities and acoustic phonons, the fit is far from being perfect. It could possibly be improved after a careful consideration of the influence of the magnetic field on the concentration of ionized impurities. Also, the influence of optical phonons (at higher temperatures) and neutral impurities (at low temperatures) should perhaps be taken into account.

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