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Absorption and emission studies of the quantum-limit cyclotron resonance linewidth in *n*-InSb

B. D. McCombe, R. Kaplan, and R. J. Wagner
Naval Research Laboratory, Washington, D. C. 20375

E. Gornik and W. Müller
Institute für Physikalische Elektronik der Technischen Hochschule, 1040 Wien, Austria
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A systematic study of quantum-limit cyclotron resonance linewidth in several *n*-InSb samples has been carried out as a function of total ionized impurity concentration, free-carrier concentration, temperature, and magnetic field in a temperature range where ionized-impurity scattering is expected to be dominant. Both far-infrared laser transmission measurements and hot-electron emission measurements were performed. The wavelength and magnetic field range investigated were 70 to 500 μm and 23 to 3 kG, respectively. The linewidth is found to be proportional to the square root of the total ionized impurity concentration, and a minimum in the linewidth as a function of magnetic field is observed in all samples. Within experimental error the magnitude of the linewidth and the magnetic field position of the minimum linewidth are independent of free-carrier concentration indicating that free-carrier screening of the ionized impurities does not play a role. These results are discussed and interpreted in light of existing theories.

I. INTRODUCTION

Several authors[1–5] have recently pointed out that cyclotron resonance linewidth studies in the far infrared promise to yield detailed information about carrier scattering mechanisms in semiconductors. Thus far, however, a large number of investigations, both experimental and theoretical, have produced a bewildering variety of (sometimes contradictory) results. Even for the relatively simple case of low-temperature cyclotron resonance measurements under extreme quantum-limit conditions ($\hbar\omega_c \gg k_B T, E_F$) the situation remains unclear. For this case only one scattering mechanism (ionized impurity) and two energy levels (the lowest two Landau levels) are dominant in the scattering and the electric dipole transition.

In this paper we report new insights into this problem derived from a systematic study of the effects of ionized-impurity concentration, carrier concentration, magnetic field, and temperature on the cyclotron resonance linewidth in a number of *n*-InSb samples under extreme quantum-limit conditions. Both laser transmission and hot-electron emission measurements were carried out. The experimental results presented in Sec. III are summarized as follows: (i) At high fields the linewidths are proportional to $\sqrt{n_i}$, with n_i the total number of ionized impurities. (ii) The linewidth exhibits a minimum as a function of magnetic field in *all* samples. (iii) The magnitude of the linewidths and the magnetic field position of the minimum are *independent* of free-carrier concentration.

In Sec. II the relevant experimental details are briefly described, and in Sec. III the experimental results are presented and discussed.

II. EXPERIMENTAL

The magnetotransmission measurements were carried out over the wavelength range 70–500 μm (resonance magnetic fields between 23 and 3 kG) through the use of both electrical discharge and optically pumped lasers in conjuction with a superconducting magnet system. Typical data are shown in Fig. 1(a).

Hot-electron emission from Landau states was measured at liquid-helium temperatures with the aid of an InSb cyclotron resonance detector. Details of the experimental configuration have been given elsewhere.[6] Sample thicknesses were chosen to be approximately equal to the reciprocal peak absorption constant in order to avoid emission line broadening due to self-absorption.[7] Typical detector response for three emitter fields is shown in Fig. 1(b). For all magnetic fields the "doublet" structure of the detector response appears clearly; furthermore, at the highest magnetic fields two emission lines are resolved owing to spin-up and spin-down transitions (see inset).

In the emission measurements, since the observed linewidths are determined both by emitter and detector, it was necessary to extract the spectral width of the emitted radiation by deconvolution of the detector response determined from transmission measurements. This procedure was checked by performing a measurement at 2 K where the detector response consists of only a single sharp (impurity shifted cyclotron resonance) line [transition $D3$ in the inset to Fig. 1(b)]. The emission linewidth thus obtained was unchanged from that with the detector at 4.2 K.

The electrical characteristics of all the samples

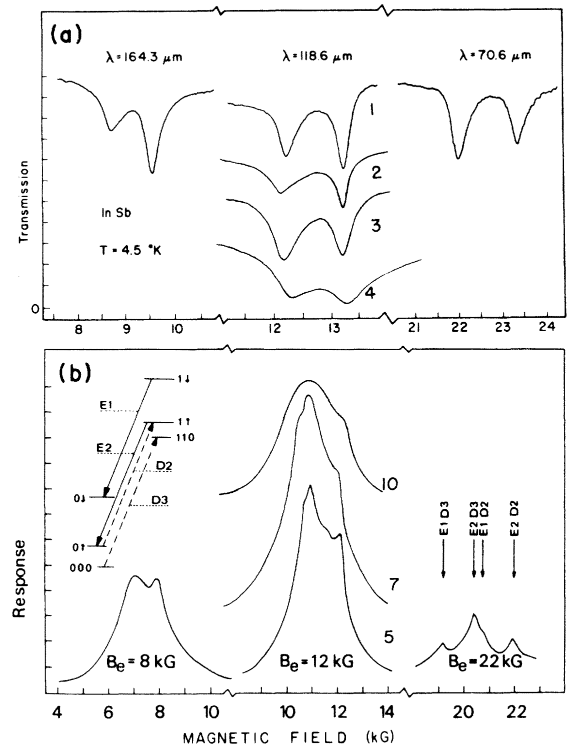

FIG. 1. (a) Magnetotransmission for several InSb samples at three laser frequencies, at 4.3 K. (b) Emission spectrum for several samples at three different fixed sample fields. The inset shows an energy level diagram for the various emitter (*E*) and detector (*D*) transitions. Transition *D*3 (000→110) is an impurity transition usually called "impurity shifted cyclotron resonance."

investigated are summarized in Table I; n_i was determined from the measured electron concentration n and the mobility μ at 77 K.[8,9]

Transmission linewidths at several frequencies were studied as a function of temperature between 4.2 and 15 K. Nonparabolicity contributions[4] were largely avoided by taking the low-field halfwidth at half peak absorption coefficient as a measure of the spectral linewidth. The linewidth thus determined was found to be independent of temperature. Similarly, the linewidth derived from the emission data, after subtraction of the nonparabolicity contribution as described below, was found to be temperature independent up to 30 K. Thus we conclude that phonon scattering is unimportant in this temperature range, and the linewidth is determined exclusively by ionized impurity scattering.

III. RESULTS AND DISCUSSION

A. n_i dependence

Linewidths (converted to frequency units) obtained from both experimental techniques are plotted as a function of $\sqrt{n_i}$ in Fig. 2. The applied electric field of 4 V/cm in the emission experiments produces an electron temperature of about 20 K, and as a result, the strong nonparabolicity produces an additional broadening. This contribution to the linewidth was calculated according to the Bowers and Yafet model[10] for electron temperatures between 4.2 and 30 K,[11] and was found to be small at 4.2 K but significant for the electron temperatures present in the emission experiments. For an electron temperature of $T_E = 20$ K the lines are broadened by 0.5 cm^{-1} at 12 kG and 0.6 cm^{-1} at 22 kG. Emission linewidths corrected for nonparabolicity are plotted in Fig. 2 as the triangles; transmission data are shown as squares. The linewidths obtained by the two techniques are in excellent agreement and are well represented within experimental error by $\Gamma_{1/2} = \text{const.} \times \sqrt{n_i}$.

This square-root dependence of the linewidth on n_i is predicted by several theoretical calculations[2,3,5,12]; it is essentially due to the fact that an electron scattering from a given impurity is a quasiparticle with a finite lifetime due to the influence of other impurities. When the quasiparticle lifetime is taken into account in the appropriate

TABLE I. Sample parameters. The quantities n, μ, and n_i are defined in the text. $(n_i)^{-1/3}$ is the average impurity separation; $r_s = (\hbar/2m^*\omega_p)^{1/2}$ is the screening length,[3] with $\omega_p = (4\pi n e^2/m^*\epsilon_B)$; and ϵ_B the background dielectric constant.

Designation	$n = N_D - N_A$ (77 K) (10^{13} cm^{-3})	μ(77 K) (10^5 $cm^2\,V^{-1}\,sec^{-1}$)	$n_i = N_D + N_A$ (10^{14} cm^{-3})	$(n_i)^{-1/3}$ (Å)	r_s (Å)
1	7.	7.5	3.28	1453	790
2	0.45	6.5	4.0	1357	1570
3	15.	5.0	6.9	1132	655
4	60.	3.2	18.6	813	460
5	8.0	7.0	4.2	1335	765
6	5.0	5.4	6.3	1167	860
7	0.80	3.7	8.0	1077	1360
8	20.	5.0	7.0	1126	610
9	67.	3.0	20.	794	450
10	40.	2.4	27.	718	510

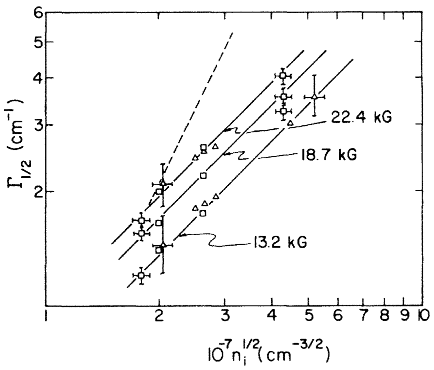

FIG. 2. Cyclotron resonance linewidths (converted to frequency units) as a function of the square root of the total ionized impurity concentration for three different values of magnetic field. Squares, transmission data; triangles, emission data. Solid lines drawn through the data have a slope of 1, i.e., $\Gamma_{1/2} \propto n_i$. The dashed line has a slope of 2 for comparison purposes.

energy denominators, under approximations valid for the experimental situation, the *square* of inverse lifetime for scattering between adjacent Landau levels is directly proportional to the ionized impurity concentration.[13]

B. Magnetic field dependence

The magnetic field dependence of the linewidth from laser transmission measurements on four samples is shown in Fig. 3. Note that there is a definite minimum for all samples. Within the experimental error there is no discernible shift in the magnetic field position of the minimum for samples 1, 2, and 3. The minimum for sample 4 is shifted to higher fields. The emission measurements exhibited an increase in linewidth between 12 and 22 kG in qualitative agreement with the above; however, owing to the larger error inherent in these measurements, variations in the linewidth between 8 and 12 kG could not be determined.

The linewidth minimum is not contained, either explicitly or implicitly, in any of the published theoretical treatments. Shin *et al.*[2] predict a linewidth that increases monotonically throughout the region $\ell/a > 1$ to $\ell/a \ll 1$ where a is the range of the model potential used. In contrast, the calculation of Lodder and Fujita yields a *maximum* in linewidth near[5,13] $\ell/a = 1$, and a *decreasing* width with field for $\ell/a \ll 1$. (A decreasing width in this region was also obtained by Kawabata.[1]) In the former calculation[2] the transport "scattering-in" and "scattering-out" terms, which have the effect of slowly reducing the influence of small-wave-vector (q) Fourier components of the scattering potential, were not included. It is precisely the small-q components that predominate in this calculation and determine the magnetic field behavior. Transport terms were explicitly included in the calculations of Refs. 1, 5, and 13; however, Argyres and Sigel[14] have recently criticized these theories and conclude that these results do not provide an adequate description of the linewidth in the region of interest, $\omega_c \approx \omega$. Argyres and Sigel derive a formal expression for the line shape in terms of a matrix-integral equation which is, unfortunately, not evaluated. On the other hand, a recent Green's function treatment, which considers the scattering in the framework of the generalized Born approximation and which includes the transport terms, does yield a linewidth minimum near $\ell/a = 1$ for a Gaussian model potential of range a.[12]

In spite of the varied theoretical results, we believe that the linewidth minimum is indeed related to matching the cyclotron orbit size with the effective range of the potential ($\ell/a \approx 1$). It appears that the minimum results from a subtle interplay between inter- and intra-Landau level scattering. The relative importance of these processes is a function of magnetic field since (i) the scattering potential is strongly q dependent (the Fourier components drop off rapidly for $q > 1/a$), and (ii) the matrix elements of the potential between Landau functions exhibit sharp structure (edges or peaks) at values of q approximately equal to $1/\ell$ and multiples thereof.[15]

C. Free-carrier concentration dependence

A final question raised by these experiments is concerned with the apparent lack of sensitivity of the linewidth to free-carrier concentration (screen-

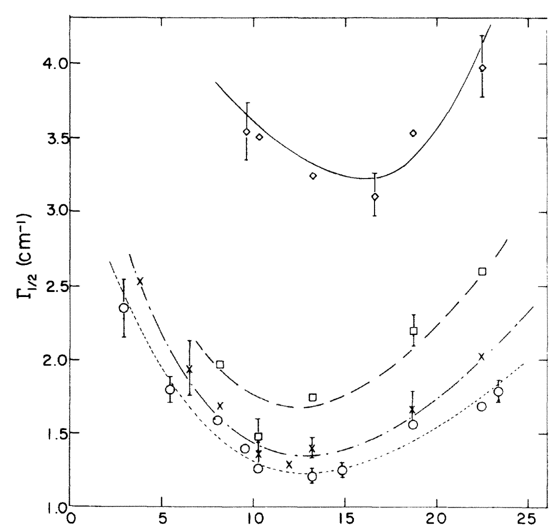

FIG. 3. Plot of cyclotron resonance linewidth as a function of resonance magnetic field for the four absorption samples: ○, 1; ×, 2; □, 3; and ◇, 4.

ing). A good example of this is seen by comparing the linewidths for samples 1 and 2, for which n_i differs by only 20% while n for 1 is roughly 15 times that of 2 (Table I). If screening of the ionized impurities by free carriers were important, it should be clearly evidenced in the variation of linewidth between these samples. Theoretical calculations[2,3,5] which consider screened ionized impurity scattering in the limit $\ell/r_s \ll 1$, where $\ell = \sqrt{c\hbar/eB}$, and r_s is the screening length, predict $\Gamma_{1/2} \propto n_i^{1/2}/n^{1/4}$. Based on these results the linewidth for 2 should be more than a factor of 2 greater than that of 1; in contrast the experimental ratio is only 1.1, and is completely accounted for by the n_i dependence. Similarly, no influence of the electron concentration on the linewidth was observed in the emission measurements for samples having nearly the same total impurity content but a free-carrier concentration differing by a factor of 25 (7 and 8 of Table I). In addition, the increase in linewidth at constant magnetic field for the other samples is adequately accounted for by the increase in n_i alone. It should be noted in this regard that the calculated screening lengths do not differ appreciably from the average interimpurity separations for the samples investigated (Table I). Thus the isolated impurity model may not be a good approximation, and the range may be related to the average impurity separation; in addition, the single site scattering model utilized in all the theories is subject to question.

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[1]A. Kawabata, J. Phys. Soc. Jpn. 23, 999 (1967).

[2]E. E. E. Shin, P. N. Argyres, and B. Lax, Phys. Rev. B 4, 3572 (1973).

[3]E. E. H. Shin, P. N. Argyres, N. M. Horing, and B. Lax, Phys. Rev. B 7, 5408 (1973).

[4]R. Kaplan, B. D. McCombe, and R. J. Wagner, Solid State Commun. 12, 967 (1973).

[5]A. Lodder and S. Fujita, J. Phys. Soc. Jpn. 25, 774 (1968); Phys. Lett. A 46, 381 (1974).

[6]E. Gornik, W. Müller, and F. Kohl, IEEE Trans. Microwave Theory Tech. MTT22, 991 (1974).

[7]Earlier studies by E. Gornik, W. Müller, and F. Kohl in [*Proceedings of the Twelfth International Conference on the Physics of Semiconductors* (Teubner, Stuttgart, 1974), pp. 839–843] yielded artificially broadened lines.

[8]D. L. Rode, Phys. Rev. B 3, 3287 (1971).

[9]D. Kranzer and E. Gornik, Solid State Commun. 9, 1541 (1971).

[10]R. Bowers and Y. Yafet, Phys. Rev. 115, 1165 (1959).

[11]W. Müller and E. Gornik (unpublished).

[12]M. Häuser, thesis (University of Cologne, 1975) (unpublished).

[13]A. Lodder [Solid State Commun. 16, 117 (1975)] has pointed out that the nelgect of a q-dependent term in the energy denominators as was done in the calculations of Refs. 2 and 4 is not justified. He obtains an $n_i^{2/3}$ dependence for the linewidth when the integration is carried out over q parallel to the magnetic field. This is not in agreement with our experimental results, and it appears that the neglect of this term is justified when conservation of energy and momentum for the scattered electron is taken into account.

[14]P. N. Argyres and J. L. Sigel, Phys. Rev. B 10, 1139 (1974).

[15]See for example, J. J. Quinn and S. Rodriguez, Phys. Rev. 128, 2487 (1962).