Observation of Impurity Cyclotron Resonance in $Hg_{1-x}Cd_xTe$

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Impurity cyclotron resonance (ICR) has been observed in n-$Hg_{1-x}Cd_xTe$. This experiment provides conclusive evidence for donor-bound electrons in this semiconductor. The separation between the ICR and the free-carrier resonance is in satisfactory agreement with theoretical predictions for hydrogenic donors in a strong magnetic field. Saturation of the ICR absorption was used to determine the electron lifetimes of $\sim 10^{-6}$ sec in the lowest Landau level.

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The electronic ground state of n-type semiconducting $Hg_{1-x}Cd_xTe$ ($x \sim 0.2$) in strong magnetic fields has been controversial for over fifteen years. Several groups have reported evidence for an electronic phase transition into a Wigner lattice.[1] Others have reported evidence for Anderson localization,[2] a charge-density wave,[3] and magnetic freezeout.[4] Some of these interpretations were based on the assumption that the conduction-band electrons come not from shallow donors but from donor states resonant with the conduction band.[5] This controversy is a consequence of the absence of direct (e.g., spectroscopic) evidence for donor-bound electrons in $Hg_{1-x}Cd_xTe$. This situation is particularly surprising in view of the case of InSb which has a similar electronic structure.

Impurity cyclotron resonance (ICR) is an optically induced transition of a donor-bound electron from the ground state, related to the lowest ($N=0$, spin-up) Landau-level states, to an excited bound state, related to the $N=1$, spin-up Landau level. The energy separation of the donor-bound states is slightly greater than that of the Landau levels and, therefore, ICR is shifted from the free-carrier resonance. The first observation of impurity cyclotron resonance was reported[6] for InSb in 1957 and this phenomenon has been studied extensively since then.[7-10]

In this Letter we report the observation of ICR in $Hg_{1-x}Cd_xTe$—the first conclusive evidence, to our knowledge, that at low enough temperatures and sufficiently high magnetic fields the conduction-band electrons are bound on donors. This direct observation contradicts the recent interpretations of transport measurements in $Hg_{1-x}Cd_xTe$ in terms of Wigner condensation of the electrons.[1] The energy splitting between the ICR and the conduction-band cyclotron resonance (CCR) is consistent with calculations performed within the hydrogenic donor model[11,12] and can be used to determine the binding energy of the electrons. The saturation of the ICR absorption with the incident radiation intensity, previously studied[8-10] in InSb, was used here to measure the lifetime of the electrons accumulating in the lowest Landau level, $T_1 \sim 10^{-6}$ sec—nearly two orders of magnitude longer than in InSb.

High-quality single crystals of $Hg_{1-x}Cd_xTe$ were grown at Honeywell Electro-Optics Division. Samples were cut from 15-mm-diam wafers, polished, and briefly etched in a 3% bromine-methanol solution minutes before being mounted in the cryostat. Properties of the samples[13] are listed in Table I. Measurements were made in Faraday configuration with use of far-infrared (FIR) radiation from an optically pumped cw laser. The radiation was circularly polarized with use of a FIR linear polarizer and a crystal quartz $\lambda/4$ plate and was detected by a Ge:Ga composite bolometer. The samples were mounted on a wedged germanium substrate and were immersed in pumped liquid ^{4}He to achieve temperatures below 4 K. A FIR absorber with a small (3-mm-diam) hole was placed immediately in front of the samples to ensure the uniformity of the incident radiation.

Typical magnetotransmission spectra are shown in Fig. 1. The ICR absorption decreases and the CCR absorption increases as the temperature [Fig. 1(a)] or the radiation intensity [Figs. 1(b) and 1(c)] is raised. There is no ICR absorption in the cyclotron-resonance–inactive circular polarization within the experimental uncertainty of $\sim 2\%$, in agreement with the theoretical prediction[11] that the selection rules for the two processes are the same.

From the transmission data we calculated αd, where $\alpha(B)$ is the absorption coefficient and d is the sample

TABLE I. Properties of $Hg_{1-x}Cd_xTe$ samples.

Sample	x	E_g [a] (meV)	n (cm^{-3})	μ [b] ($cm^2/V\cdot sec$)	d (μm)
0.204-3N13A	0.204	75	3×10^{13}	2.7×10^5	305
0.204-3N13B					290
0.224-6N13	0.224	105	6×10^{13}	1.2×10^5	260

[a]Energy gap (at 4 K) was calculated from the empirical expression of Schmit and Stelzer (Ref. 14).
[b]Mobility measured at 77 K.

thickness. We neglected multiple reflections because of the substrate. At high temperatures (~ 10 K) where only CCR is present, the data can be fitted reasonably well with a Lorentzian absorption line, which indicates high compositional uniformity of the samples. The linewidth is consistent with the 77-K Hall mobility. From the low-temperature experimental absorption we subtract a Lorentzian line with the resonance field B_{CCR} and the halfwidth Γ from the high-temperature fit and use the peak CCR absorption α_C as a fitting parameter to get a smooth, approximately Lorentzian ICR absorption.[15] We estimate the resulting uncertainty in the resonance-field splitting, $B_{CCR}-B_{ICR}$, as 25 G for $x=0.224$ and 15 G for $x=0.204$. The peak absorption $\alpha_I d$ is accurate to within 5%–10%.

The resonance fields, B_{CCR} and B_{ICR}, are plotted versus photon energy $\hbar\omega$ in Fig. 2(a); the lines show a nonparabolic, Bowers-Yafet model[16] calculation with the band-bottom effective mass $m^*(B=0)$ used as a fitting parameter. The energy splitting between the ICR and CCR,[17] $\Delta=(E_{110}-E_{000})-(E_{1+}-E_{0+})$, was calculated from

$$\Delta(B)\simeq[d(E_{1+}-E_{0+})/dB]_{B=B_{CCR}}(B_{CCR}-B_{ICR}),$$

and is shown in Fig. 2(b). The lines in Fig. 2(b) give results of Larsen's nonparabolic model calculation,[12] adapted for our samples by use of m^* given in Fig. 2(a) and the static dielectric constant $\epsilon=17.5$. In the experimental range of magnetic fields the data are in qualitative agreement with the theory[12] developed for an isolated donor. The quantitative discrepancy ($\sim 20\%$) is similar to that observed in InSb samples.[7,18]

Figure 3 gives the dependence of the peak ICR absorption, $\alpha_I d$, on the FIR radiation intensity I. A three-level model[8] predicts

$$\alpha_I(I)/\alpha_I(0)=\{1+[\alpha_I(0)I/\hbar\omega n]T_1\}^{-1}, \quad (1)$$

where T_1 is related to the electronic lifetime of the 0^+ Landau level. In this model the electrons are excited

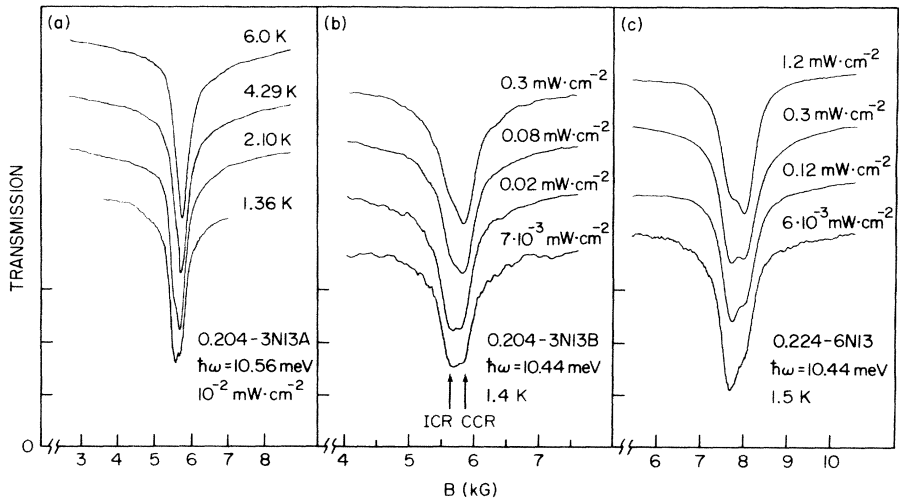

FIG. 1. Magnetotransmission spectra of n-$Hg_{1-x}Cd_xTe$ samples at different temperatures and FIR radiation intensities. The arrows show the absorption peak assignment. Zero transmission levels, corrected to 100% cyclotron-resonance–active circular polarization, are shown by horizontal tick marks on the left-hand axis for each respective trace.

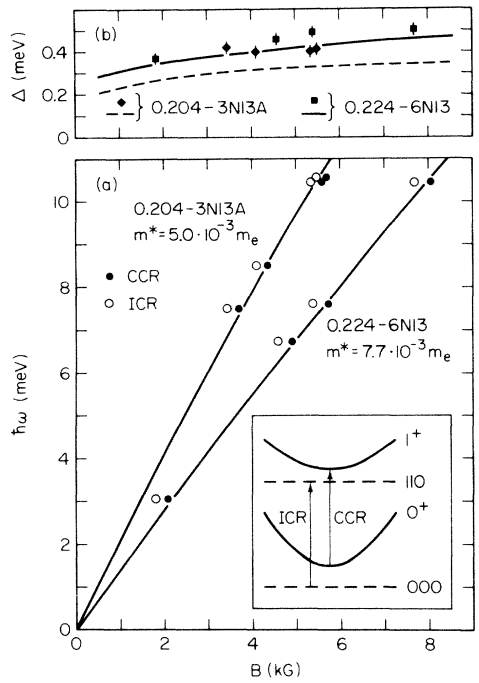

FIG. 2. (a) Resonance magnetic fields at several FIR photon energies $\hbar\omega$. The lines give nonparabolic fits for the $0^+ \rightarrow 1^+$ transition, with m^* used as fitting parameter. The inset shows the relevant energy-level scheme. (b) The energy splitting $\Delta = \hbar\omega_{ICR} - \hbar\omega_{CCR}$ vs magnetic field. The lines show scaled theoretical predictions of Ref. 12. Effective Rydberg constants for samples 0.204-3N13A and 0.224-6N13 are respectively 0.25 and 0.38 meV.

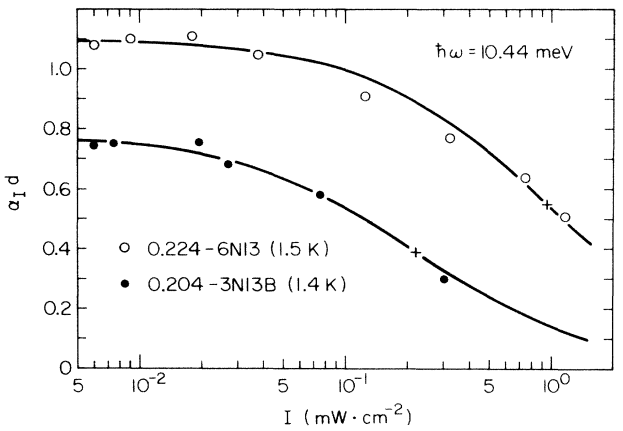

FIG. 3. Measured peak ICR absorption of the samples as a function of FIR radiation intensity. The curves are fits of Eq. (1) with the sample parameters given in Table I and in the text. Crosses denote intensities $I_{1/2}$ such that $2\alpha_I(I_{1/2}) = \alpha_I(0)$. The fits give times $T_1 = 3.4\times10^{-6}$ sec and 1.6×10^{-6} sec for samples 0.204-3N13B and 0.224-6N13, respectively.

by the FIR radiation from the (000) state to the (110) state from which they relax to the 0^+ level and directly to the ground state (000) with time constants τ_{32} and τ_{31}, respectively. If we denote the lifetime of the 0^+ Landau level by τ_{21} and make the same assumptions as in Ref. 10 ($\tau_{32} \ll \tau_{31}, \tau_{32} \ll \tau_{21}$), then at low enough temperatures $T_1 \simeq \tau_{21}$.

The reported lifetimes[8,10] for InSb ($m^* = 0.0139m_e$, $\epsilon = 14.8$) fit the empirical relation $T_1 \simeq 2.5\times10^{-9}\gamma$ sec, where $\gamma = (a^*/l_m)^2$ and the magnetic length $l_m = (c\hbar/eB)^{1/2}$. For sample 0.224-6N13 we obtained $T_1 \simeq 1.0\times10^{-7}\gamma$ sec, and for 0.204-3N13B $T_1 \simeq 1.4\times10^{-7}\gamma$ sec, that is, substantially longer lifetimes. We believe that the relative uncertainty in values of I is $\sim 10\%$; however, the absolute calibration of FIR intensity is accurate only to within a factor of 2. A more extensive study in this alloy semiconductor can determine the band-gap/effective mass dependence of the inelastic lifetimes of the lowest Landau level and the chemical shifts[18] in the donor binding energies.

Several factors combine to make the experimental observation of ICR and data analysis more difficult for $Hg_{0.8}Cd_{0.2}Te$ than for InSb. Lower electron effective mass and low $\hbar\omega_{LO} = 17$ meV limit the measurements to lower magnetic fields, which, in turn, combined with a smaller effective Rydberg constant, leads to smaller relative splitting between ICR and CCR and requires lower experimental temperatures and impurity concentrations. The alloy potential fluctuations may broaden both ICR and CCR. In addition, as is well known,[19] the surface of $Hg_{1-x}Cd_xTe$ attracts electrons from the bulk. We have performed a study of this phenomenon using CR absorption to determine the fraction of the electrons left in the bulk. It has been found that with our sample preparation procedure the bulk electron concentration per square decreased linearly with the sample's thickness as $N = nd - N_s$, where $N_s \simeq 6\times10^{11}$ cm^{-2} was concluded to be the surface electron density. Since the width of CCR did not change appreciably as a sample was thinned, down to $N \simeq 3\times10^{10}$ cm^{-2}, we also concluded that the bulk concentration n does not change, but rather that the surface electrons leave behind depletion layers at each side of the sample.

We note here that the cyclotron resonance of an accumulation layer would be shifted to higher fields by nonparabolicity and, more important, would be much broader than the bulk CCR because of the high scattering rate of the surface electrons. Indeed, we do observe a weak and broad background absorption in the magnetotransmission data.

Shorting of the bulk by the surface conduction[20] prevented us from obtaining useful transport data in these low-n samples. However, by extrapolation from the data on higher-n samples[4,21] we can estimate that the magnetic-field–induced metal-insulator transition field, B_{MI}, for sample 0.224-6N13 is approximately 3.5

kG. The FIR data at $\hbar\omega = 2.99$ meV show the ICR absorption present at a lower field (cf. Fig. 2) with the integrated absorption strength equal to that at higher fields within the experimental uncertainty. This experimental observation does not fit into any of the metal-insulator transition pictures mentioned in the introduction and suggests that even on the metallic side of the metal-insulator transition the delocalized electrons are in donor-band states which are distinct from the conduction-band proper states. We believe that the transport data on the more highly doped samples also support this conclusion and a paper on this topic is in preparation.

We believe that the selection rules, the magnitude of the splitting, and its magnetic field dependence, together with the absorption-saturation effect, allow us to identify the low-field peak in the transmission as the $(000) \rightarrow (110)$ ICR transition which is direct and conclusive evidence for hydrogenic donors in $Hg_{1-x}Cd_xTe$. This observation allows us to conclude that the Wigner condensation of the conduction-band electrons does not occur in $Hg_{1-x}Cd_xTe$. We suggest that the magnetic-field–induced metal-insulator transition in this semiconductor takes place in the donor impurity band.

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