Intervalley cyclotron-impurity resonance of electrons in *n*-Ge

E. M. Gershenzon, S. L. Orlova, L. A. Orlov, N. G. Ptitsina, and R. I. Rabinovich

Moscow Pedagogical Institute
(Submitted June 29, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **24**, No. 3, 145–148 (5 August 1976)

A resonance predicted by Rabinovich {Fiz. Tekh. Poluprovodn. **8**, 91 (1974) [Soviet Phys. Semicond. **8**, 55(1974)]}, and due to transitions of electrons that interact elastically with impurities between Landau levels of different valleys, has been observed in Ge.

PACS numbers: 76.40.+b

A resonance connected with the "simultaneous" absorption of a photon by an electron and an elastic (due to its interaction with impurity) intervalley transition is possible in multivalley semiconductors in quantizing magnetic fields. This intervalley cyclotron-impurity resonance (IVCIR) should occur at frequencies $\omega = (l_2 + \frac{1}{2})\omega_2 - (l_1 + \frac{1}{2})\omega_1$, where ω_1, ω_2, l_1, and l_2 are the cyclotron frequen-

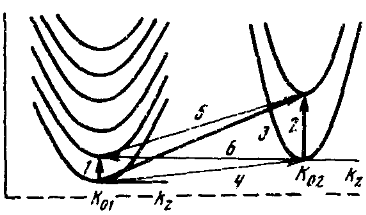

FIG. 1. Energy levels of the electrons in Ge in a quantizing magnetic field $H \parallel \langle 111\rangle$. The arrows show some of the possible transitions.

cies and the numbers of Landau levels of the two valleys in question. It is similar in nature to the cyclotron phonon[2] and intervalley cyclotron-phonon[3] resonances, but differs from them in that its frequency is not governed by the phonon spectrum of the crystal. In addition, the absorption coefficient $\alpha(\omega)$ for IVCIR can be much larger if the impurity density is high enough.[1]

The IVCIR of electrons was observed by us in Ge at submillimeter wavelengths ($\lambda = 380$—$1000\ \mu$) with the aid of a backward-wave-tube spectrometer[4] at temperatures $T = 4.2$—$2\ ^\circ$K in magnetic fields $H = 5$—20 kOe. We investigated the photoconductivity and the absorption spectra while sweeping H at fixed emission frequencies ω for samples with impurity densities $N_D - N_A = 10^{12}$—10^{15} cm^{-3} and $N_A/N_D = 1.5\%$. The free-carrier density n was determined by the background radiation of the thermal part of the cryostat and amounted to $\sim 10^9$ cm^{-3}.

The principal measurements were made at an orientation $H \parallel [111]$ in a constant bias field $E_0 \perp H$, when the cyclotron mass $m_2 = 0.0815 m_0$ of the electrons of the [111] valley was approximately 2.5 times smaller than the cyclotron mass $m_1 = 0.2 m_0$ of the remaining equivalent valleys. Figure 1 shows, for this orientation, some of the more intense transitions. Here 1 and 2 correspond to the cyclotron resonance of the electrons and 3—6 to the IVCIR. We investigated the transition 3, since the transitions 4 and 5 were close to the cyclotron resonance, and transition 6 called for $H > 100$ kOe.

Figure 2 shows by way of example the photoconductivity spectrum of a sample with $N_D - N_A \sim 3 \times 10^{15}$ cm^{-3}. The most intense line in the spectrum is CR line corresponding to the transition 2 of Fig. 1. The sought transition 3 (IVCIR) should have a resonant magnetic field $H_{res} = 0.77\ H_{CR}$. It is seen from Fig. 2 that it corresponds to the peak A, which is shown additionally in the

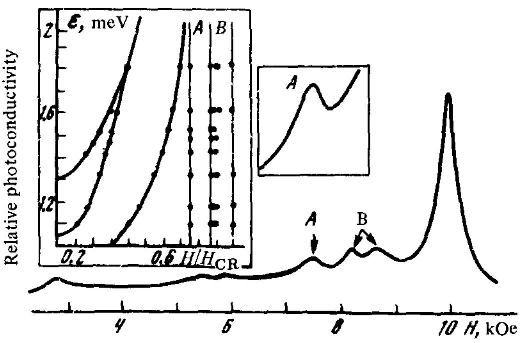

FIG. 2. Photoconductivity spectrum of sample with $N_d - N_a = 3 \times 10^{15}$ cm^{-3}. The insert shows a plot of the energies of the observed transitions against H/H_{CR}, where H_{CR} is the cyclotron-resonance field of the "light" electrons (transition 2 of Fig. 1).

same figure in an enlarged scale. In addition, several lines of approximately the same intensity have been observed. A reliable identification of the spectral line calls therefore for a detailed analysis.

It is known that in Ge, in this region of ω and H, there can exist lines due to the harmonics of the CR of the free electrons[5] and to Zeeman transitions of the electrons between the excited states of the shallow donors.[4] The insert of Fig. 2 shows plots against H/H_{CR} of the energy ϵ of all the transitions observed by us at $T=4.2\,°K$. The $\epsilon(H/H_{CR})$ plots for the cyclotron resonance harmonics, as well as for the cyclotron resonances in IVCIR, should be vertical lines; no such lines are seen for the values of H characteristic of the harmonics. The plots with the variable slopes correspond to the Zeeman components, which have at $H=0$ energies 0.71, 1.05, and 1.31 meV.[4] The peak A, which is observed at $H=(0.76—0.77)H_{CR}$ and agrees well with the theory, is attributed by us to the IVCIR. The series of lines B is observed at $H > 0.82H_{CR}$, i.e., it differs from H_{res} by an amount greatly exceeding the possible errors in the orientation, in the measurement of H, and others. This series corresponds to transitions between high-excited states of the shallow donors, for which the plot of $\epsilon(H)$ in this region of magnetic fields is determined by the nonlinear Zeeman effect and is similar to the CR plot.

A number of other arguments can be advanced to show that our determination of the nature of the peak A is correct. Temperature investigations of the photoconductivity spectra show that when the temperature is lowered the intensity of the line A increases in comparison with the remaining lines in the spectrum. This line is not observed in the spectra of pure samples ($N_D - N_A \sim 10^{12}$ cm^{-3}) and increases with increasing N_D. All the remaining lines are observed both in pure and in doped samples. In the investigation of the absorption spectra of even doped samples we have observed only the line due to CR (the absorption ad for CR was $\sim 10^{-3}$, where d is the sample thickness).

The results cited confirm that the peak A corresponds to IVCIR. Indeed, the IVCIR intensity should increase with decreasing T and with increasing N_D, in contrast to the intensity of the impurity lines when the latter are determined from the photoconductivity.[1,4] The fact that the absorption spectra do not contain IVCIR and impurity lines is not surprising: estimates of the absorption for IVCIR and the impurity lines in our samples yield a value $ad < 10^{-5}$, whereas the sensitivity of the spectrometer used by us[4] was 10^{-5}—10^{-4}. The difference between the intensities of the IVCIR and the cyclotron resonance lines in the photoconductivity and absorption spectra is due to the fact that the photoconductivity mechanisms for these resonances are different. The photoconductivity in cyclotron resonance of free electrons is the result of heating of the electrons and of the associated slight change of n or μ (μ is the mobility) following absorption of the radiation. The photoconductivity in IVCIR is due to the fact that the electrons go over from valleys with mobility-tensor components μ_{1E} into a valley with $\mu_{2E} \approx 30\,\mu_{1E}$.[6] Consequently the ratio of the intensities of the IVCIR and cyclotron-resonance peaks in the photoconductivity spectra should be much larger than in the absorption spectra.

A convincing argument favoring the correctness of the foregoing identification can be provided by measurement of the anisotropy of the effect.

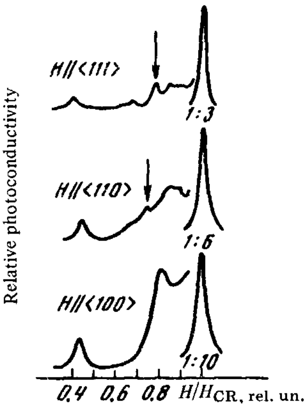

FIG. 3. Photoconductivity spectra of doped Ge sample at different orientations of H. The arrows indicate the calculated values of H/H_{CR} for the IVCIR peak; the fraction under the cyclotron-resonance indicates its scale relative to the remaining peaks in the spectrum.

Figure 3 shows the photoconductivity spectra for a doped sample at different orientations of H relative to the crystallographic axes. It is seen that at $H \parallel [100]$ this spectrum does not contain the line ascribed by us to the IVCIR. This was to be expected, since at $H \parallel [100]$ all the energy valleys of the conduction band are equivalent and no IVCIR should be observed. At $H \parallel [110]$, the IVCIR line is shifted, in agreement with theory, relative to $H \parallel [111]$ into the region of lower values of H/H_{CR}; its intensity decreases, for in this case the ratio of the electron mobilities in the "final" and "initial" valleys is less than at $H \parallel [111]$.[6]

It should be noted in conclusion that the cyclotron-resonance harmonics, which should according to our estimates have values of ad comparable with the IVCIR, are not observed in our experiments, apparently precisely because the transitions corresponding to them occur within the limits of one valley and their contribution to the photoconductivity is small.

The authors thank Yu. A. Gurevich for useful discussions.

[1]R. I. Rabinovich, Fiz. Tekh. Poluprovodn. **8**, 91 (1974) [Sov. Phys. Semicond. **8**, 55 (1974)].
[2]F. G. Bass and I. B. Levinson, Zh. Eksp. Teor. Fiz. **49**, 914 (1965) [Sov. Phys. JETP **22**, 635 (1966)].
[3]R. Bakanas, Y. Levinson, and F. Bass, Phys. Lett. **28A**, 604 (1969).
[4]E. M. Gershenzon, G. N. Gol'tsman, and N. G. Ptitsina, Zh. Eksp. Teor. Fiz. **64**, 587 (1973) [Sov. Phys. JETP **37**, 299 (1973)]; E. M. Gershenzon, L. A. Orlov, and N. G. Ptitsina, Pis'ma Zh. Eksp. Teor. Fiz. **22**, 207 (1975) [JETP Lett. **22**, 95 (1975)].
[5]Yu. A. Gurvich, Zh. Eksp. Teor. Fiz. **61**, 1120 (1971) [Sov. Phys. JETP **34**, 598 (1972)].
[6]I. M. Tsidil'kovskiĭ and V. P. Shirokovskiĭ, Fiz. Metal. Metalloved. **IX**, 321 (1960).