hydrogen in many properties that depend on the principal quantum number n. However, when properties connected with other quantum numbers (ℓ, n_1, n_2) are considered, noticeable differences appear between hydrogen and other elements.

[1] N. V. Fedorenko, V. A. Ankudinov, and R. N. Il'in, Zh. Tekh. Fiz. 35, 585 (1965) [Sov. Phys.-Tech. Fiz. 10, 461 (1965)].
[2] S. E. Kupriyanov, Zh. Eksp. Teor. Fiz. 55, 460 (1968) [Sov. Phys.-JETP 28, 240 (1969)], ZhETF Pis. Red. 5, 197 (1967)].
[3] R. N. Il'in, B. I. Kikiani, V. A. Oparin, E. S. Solov'ev, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. 47, 1235 (1964) [Sov. Phys.-JETP 20, 835 (1965)].
[4] A. C. Riviere and D. R. Sweetman, Comptes rendus de la VI Conference internationale sur les phenomenes d'ionisation dans les gaz, 1963, Paris, V. I. p. 105.
[5] A. H. Futch and C. C. Damm, Nucl. Fusion, 3, 124 (1963).
[6] R. N. Il'in, V. A. Oparin, E. S. Solov'ev, and N. V. Fedorenko, ZhETF Pis. Red. 2, 310 (1965) [JETP Lett. 2, 197 (1965)], Zh. Tekh. Fiz. 36, 1241 (1966) [Sov. -Tech. Phys. 11, 921 (1967)].
[7] E. S. Solov'ev, R. N. Il'in, V. A. Oparin, and N. V. Fedorenko, Zh. Eksp. Teor. Fiz. 53, 1933 (1967) [Sov. Phys.-JETP 26, 1097 (1968)].
[8] V. A. Oparin, R. N. Il'in, and E. S. Solob'ev, ibid. 52, 369 (1967) [25, 240 (1967)].
[9] J. R. Hiskes, Phys. Rev. 137 A, 361 (1965); Phys. Lett. 15, 42 (1965).
[10] H. A. Bethe and E. E. Salpeter, Quantum mechanics of one- and two -electron atoms, Berlin 1957.

RESONANT ABSORPTION, SCATTERING, AND EMISSION OF ELECTRON-HOLE DROPS IN GERMANIUM IN THE REGION OF THEIR PLASMA FREQUENCY

V. S. Vavilov, V. A. Zayats, and V. N. Murzin
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 11 August 1969
ZhETF Pis. Red. 10, No. 7, 304 - 309 (5 October 1969)

It is indicated in [1] that formation of a new phase, namely an electron-hole condensate of a metallic type, is possible in a large-radius exciton system with high exciton concentration and at sufficiently low temperatures. Experimental observation, in the region of interband transitions, of the condensed phase in germanium, as revealed by optical observation was reported in [2] and [3]. We have investigated the optical properties of the condensed state in germanium in the far infrared (IR), i.e., in the region of possible plasma resonance.

The experiments were performed on p-Ge samples with residual impurity density $\sim 1 \times 10^{12}$ cm^{-3}, area 2 - 4 cm^{2}, and thickness $d = 0.04$ cm, immersed in liquid helium. The electron-hole pairs were produced by radiation from a 100-W incandescent lamp (through a KDP filter); the radiation power was determined with an IMO-1 calorimeter. In the absorption investigations, the directly-measured quantity was the ratio of the transmission of the optically-excited sample to its dark transmission in the wavelength range from 60 to 1000 μ [4, 5].

The indicated measurements, made in a rather wide far-IR spectral range, revealed a decrease in the transmission of germanium optically excited at low temperature ($T \leq 1.6$°K). The character of the decrease in the transmission was such that it could not be connected with absorption by free carriers or with plasma reflection. Nor could it be attributed to absorption by compensated impurities in the samples. The measurement results recalculated in terms of the quantity αd, i.e, the decrease of the intensity of the long-wave IR passing through the sample, are shown in Fig. 1. It is seen from the figure that the measured spectrum has

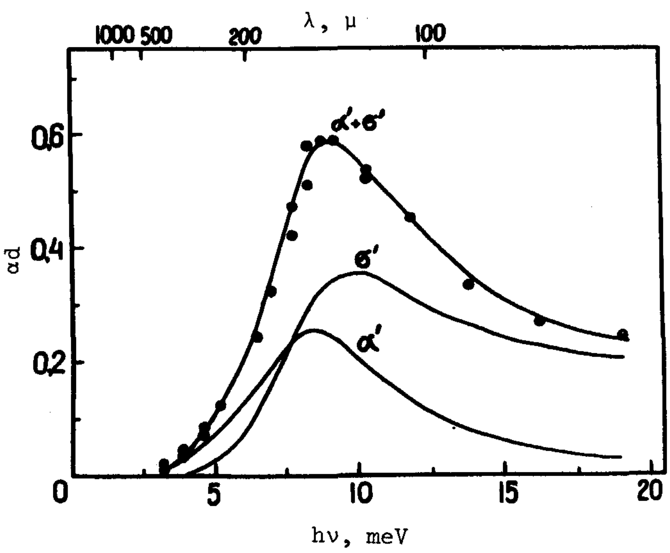

Fig. 1. Spectral dependence of αd. The experimental points were obtained at T = 1.5°K and I = 300 mW. Solid lines - calculated curves: α'- absorption coefficient inside sample, σ' - scattering cross section, (α' + σ') - summary curve.

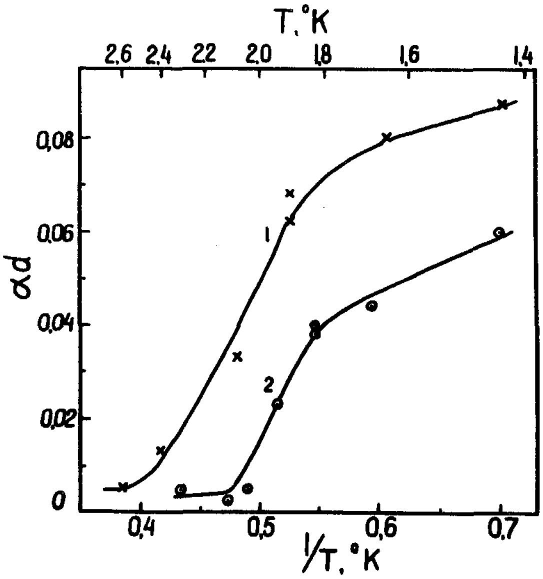

Fig. 2. Temperature dependence of αd, measured at λ = 190 μ for different excitation levels: 1 - I = 75 mW, 2 - I = 50 mW.

a resonant character with a maximum at a photon energy ∿ 8.7 meV, with a gently sloping short-wave wing. When the illumination power is reduced to 100 mW, the form of the spectrum does not change noticeably, and the maximum remains in place at practically the same energy. Figure 2 shows the temperature dependences of the effect at two excitation levels. It is seen that when the temperature is increased the effect decreases quite rapidly, and drops almost to zero at 2 - 2.5°K. In addition, the limiting temperature depends strongly on the excitation level. The threshold character of the described phenomenon is observed also in the dependence of the quantity αd on the intensity I of the exciting radiation. At low excitation intensities the effect increases rapidly ($\alpha d \sim I^3$), followed by a more gently sloping nearly-linear section.

Since the observed effect occurs at a definite excitation level and exists at temperatures below a certain limit, it can be assumed to be connected with the formation of the condensed electron-hole phase. The fact that the spectral dependence of αd has a resonant character which leads to the conclusion that this phase exists in the form of electron-hole drops, and the decreased transmission is the result of resonant absorption and scattering of the long-wave IR radiation by the electron-hole drops (dipoles) with a natural frequency that is determined by their plasma oscillations. The drop dimensions should be smaller than the wavelength in this case.

The obtained data and the theory of dipole absorption and scattering [6] make it possible to determine certain parameters of the electron-hole drops and to separate the two effects. Such calculations were made on the assumption that the attenuation coefficient of the drop oscillations does not depend on the frequency (Fig. 1). The most interesting parameter, determined at T = 1.5°K and I = 300 mW, is the plasma frequency of the drops, $\omega_{pl} = \sqrt{3}\omega_0 = 2 \times 10^{13}$ sec^{-1} (assuming spherical drops with natural frequency ω_0), and the corresponding density of the electron-hole pairs in the drop, $n_0 = 2 \times 10^{17}$ cm^{-3}. Since the position of the αd maximum remains invariant at different excitation levels (from 100 to 300 mW), it follows that the particle density in the drop remains constant, a feature characteristic of drop condensation. The measurement data make it also possible to determine the effective frequency ($\gamma = 9 \times 10^{12}$ sec^{-1}) of the collisions that lead to attenuation of the plasma oscillations in the drop. The interaction with the phonons at T ∿ 100°K, corresponding to an oscillation energy hν ∿ 10^{-2} eV, yields a value of γ of the same order. However, when the carrier density in the drop is ∿ 10^{17} cm^{-3}, the electron-electron interaction can yield, according to the estimates, a contribution of the same magnitude (and perhaps even larger) to the damping of the plasma oscillations. In this case γ increases with the frequency, and the results of the calculations change somewhat, indicating an increased role of absorption in the total effect. The measurement results yielded the approximate drop dimensions ($r_0 \approx 10 - 20$ μ), their total number in the sample ($f \approx 3 \times 10^3$), and also the condensed-carrier averaged over the volume ($n_{av} \approx 2 \times 10^{14}$ cm^{-3}). The relatively small total number of drops in the samples gives grounds for assuming that the possible condensation centers are dislocations, whose density in our samples amounted to ≥ 10^3 cm^{-2}.

It was natural to attempt to observe, in the same spectral range, the radiation resulting from thermal excitation of plasma oscillations of the electron-hole drops. Registration of such radiation would make it possible to estimate the drop temperature. This is of interest because, according to some data [7], the interaction of electron-hole drops with the crystal lattice should be attenuated by the Fermi degeneracy of the carriers. The capture of the free excitons are recombination of the carriers in the drop can therefore cause the drop temperature to considerably different from the lattice temperature.

In the very first experiments performed at T ≤ 1.6°K, intense integral radiation was observed at λ > 60 μ. Figure 3 shows the experimental data on the spectral distribution of

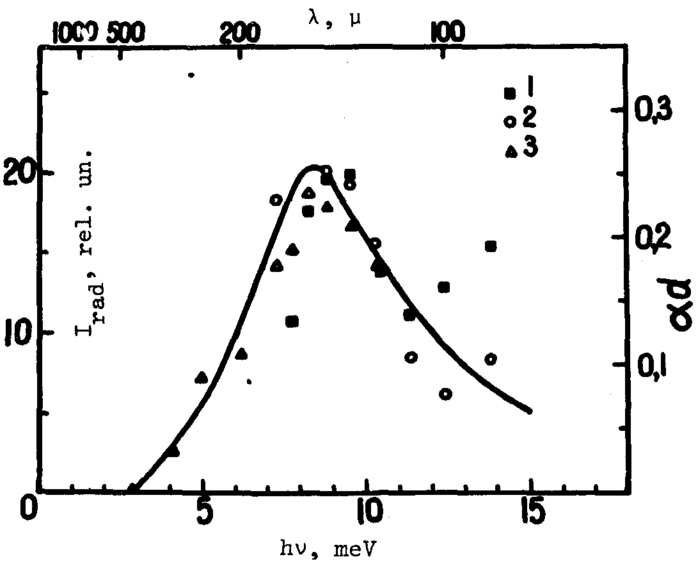

Fig. 3. Radiation of electron-hole drops at 1.5°K and at an excitation power I = 300 mW, referred to Δν= 1 cm^{-1}: 1 - from comparison with radiation of PRK-4 lamp; 2, 3 - with allowance for the distribution of echelettes of 6 lines/mm (2) and 2 lines/mm (3). The solid line shows the resonance absorption coefficient α', taken from Fig. 1.

the radiation, measured with a long-wave IR spectrometer [4] and recalculated to allow for the echelette distribution function, or compared with the radiation from a PRK-4 lamp in the far IR [8]. We see that the radiation data lie close to the resonance-absorption curve determined for the same conditions. The radiation maximum is approximately in the region of the plasma frequency of the drops. The measured dependences of the radiation intensity on the temperature and on the excitation level exhibited a threshold behavior, just as in the transmission measurements. All these facts allow us to state that the observed radiation is dipole radiation of electron-hole drops, resulting from thermal excitation of plasma oscillations in the drops.

On the basis of the obtained data, with allowance for the measured absorption coefficient of the electron-hole drops in the region of their plasma frequency, we can estimate the drop temperature by considering the drop as a quasi-equilibrium system and using Kirchhoff's law. The effective drop temperature determined in this manner is quite high, 12 - 15°K. This agrees quite well with the theoretical boiling temperature of the drops, $T_{theor} \sim 10^{\circ}K$, which can be estimated from the energy difference of the electron-hole pairs in an exciton gas and in the condensed phase ($\Delta E \simeq 4.6$ meV according to the data of [3]). It is quite probable that under the experimental conditions the electron-hole drops are in the boiling state.

We note that the described phenomena were observed, with some differences, in other germanium samples, including some doped up to a density $\sim 7 \times 10^{15}$ cm^{-3}.

The authors are grateful to B. M. Vul for interest in the work and to L. V. Keldysh for a detailed discussion of its results and for certain estimates.

[1] L. V. Keldysh, Proc. IX International Conf. on the Physics of Semiconduct., Moscow-Leningrad, 1969 p. 1307.
[2] V. M. Asnin and A. A. Rogachev, ZhETF Pis. Red. 9, 415 (1969) [JETP Lett. 9, 248 (1969)].
[3] Ya. E. Pokrovskii and K. I. Svistunova, ibid. 9, 435 (1969) 9, 26 (1969)].
[4] A. I. Demeshina and V. N. Murzin, Opt. spekrosk. 13, 826 (1962).
[5] V. V. Buzdin, A. I. Demeshina, and V. N. Murzin, PTE No. 1, 235 (1969).
[6] L. D. Landau and E. M. Lifshitz, Teoriya polya, Fizmatgiz, 1960 [Classical Theory of Fields, Addison-Wesley, 1963].
[7] V. S. Bagaev, T. I. Galkina, O. V. Gogolin, and L. V. Keldysh, ZhETF Pis. Red. 10, 309 (1969) [this issue, next article].
[8] A. E. Stanevich and I. G. Yaroslavskii, Opt. mekh. prom. 5, No. 1 (1966).

MOTION OF ELECTRON-HOLE DROPS IN GERMANIUM

V. S. Bagaev, T. I. Galkina, O. V. Gogolin, and L. V. Keldysh
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 12 August 1969
ZhETF Pis. Red. 10, No. 7, 309 - 313 (5 October 1969)

The possible formation of a condensed phase of electron and holes in semiconductors at higher exciton density and at low temperatures was pointed out in [1]. Experimental observation of the condensate in germanium and in investigations of absorption and radiative recombination was reported in [2] and [3].

One of the most characteristic features of such a condensed state, namely of electron-hole (EH) drops, should be their extremely high mobility. Indeed, scattering by phonons of