Feasibility of a phase transition in a nonequilibrium electron-hole plasma in germanium

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(Submitted August 5, 1975)
Pis'ma Zh. Eksp. Teor. Fiz. **22**, No. 6, 336–339 (20 September 1975)

We investigated experimentally the absorption and dispersion of microwaves in thin and bulky samples of pure germanium following surface optical excitation. The results can be explained by means of a hypothesis that postulates the production, near the illuminated surface of the sample, of metastable dense-plasma bunches that relax into electron-hole condensate drops.

PACS numbers: 72.30., 78.70.G

We present here the results of an investigation of the absorption and dispersion of an 8-mm band wave in optically excited germanium samples at $T \leqslant 4.2\,^\circ$K, with simultaneous registration of their recombination radiation. These investigations have led us to the conclusion that a phase transition to a nonequilibrium electron-hole plasma (EHP) can occur in a layer of the sample near the surface, and plasma bunches of fixed density $\sim 5\times 10^{16}$ cm^{-3} are produced and then relax into "ordinary" exciton-condensate drops.

The experimental procedure was similar to that reported in [1,2], but the samples were excited with a cw 30-mW LG-126 laser. The light was modulated at 120 Hz, and all the signals were registered by a standard procedure.

Figure 1 shows the absorption and dispersion signals as functions of the pump. We see that at $I = I_{thr}$ a sharp increase takes place in the absorption, and the dispersion signal reverses sign. This sign reversal indicates that there have appeared in the sample regions of dense plasma with $\omega_p = (4\pi n e^2/\epsilon_0 m^*)^{1/2} \gg \omega$ (ω is the frequency of the probing wave), and these regions, as seen from Fig. 1, have appreciable absorption. As seen from Fig. 2a, the absorption produced at $I \geqslant I_{thr}$ depends little on the magnetic field, so that it can be concluded that it is due to a dense plasma with $\omega\tau_p \lesssim 1$. However, in addition to the dense plasma, there are regions where the carrier density is low. In fact, cyclotron-resonance lines are separated against the background of the absorption with $\omega\tau_p \leqslant 1$. The widths of these lines, at $I < I_{thr}$, increase with the pump, and at $I \gtrsim I_{thr}$ it then stabilizes at a value $\omega\tau_p \approx 18$ to 20 at 4.2 °K and at ≈30 at 1.8 °K. The cyclotron-resonance signal, after subtracting the contribution that does not depend on the magnetic field, saturates at $I > I_{thr}$, as does the line width. Assuming that under the experimental conditions τ_p is determined by the electron-hole scattering mechanism,[3] we can estimate the particle concentration in the rarefied plasma at $(n, p) \approx 5\times 10^{12}$ cm^{-3}.

The dispersion signals are shown in Fig. 2b. In weak magnetic fields at $I \gtrsim I_{thr}$ the dispersion signal reverses sign, thus indicating the appearance of a plasma with $\omega_p \gg \omega$ in the sample. In strong magnetic fields the dispersion signal is oscillatory. The oscillations in the dispersion signals appeared at $I \gtrsim I_{thr}$ and retained their position as the pump was increased from threshold to maximum (however, the ratio of the oscillating and monotonic components of the dispersion signal varied, and at maximum pump the contribution of the monotonic component was larger than that of the oscillating component). The positions of the oscillations

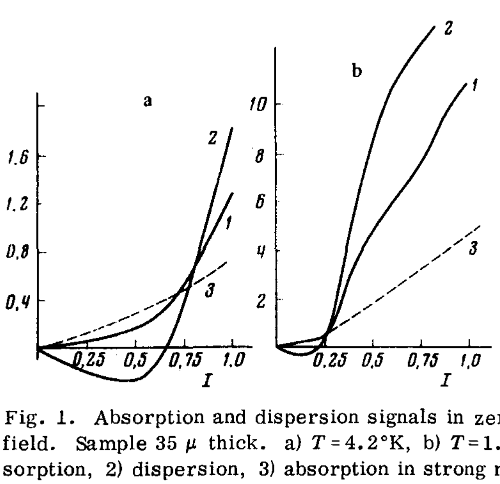

Fig. 1. Absorption and dispersion signals in zero magnetic field. Sample 35 μ thick. a) $T = 4.2$ °K, b) $T = 1.8$ °K; 1) absorption, 2) dispersion, 3) absorption in strong microwave field at a microwave power ~10 mW.

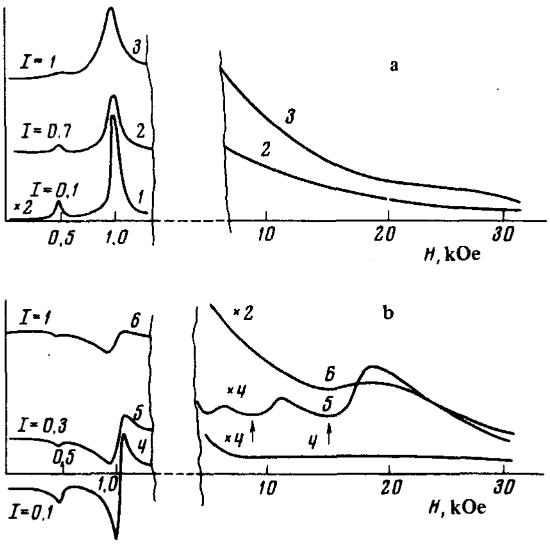

Fig. 2. Absorption (a) and dispersion (b) spectra in a magnetic field. Sample 325 μ thick, $T = 1.8\,^\circ$K. The excitation intensity (I) is indicated in units of $I_{max} = 10$ W/cm^2. The magnetic field direction coincides with the $\langle 111 \rangle$ axis.

changed with changing orientation of the sample relative to the magnetic field. As shown in [2], in the region of strong magnetic field in a dense EHP one can observe, in principle, size-effect and magnetoplasma resonances, that appear in the absorption of the microwave. These resonances, however, should not appear in practice in the dispersion signals.

In our opinion, the observed oscillations of the dispersion signal can be interpreted as a manifestation of the Shubnikov–de Haas effect. A similar behavior of the dispersion signal was observed in [4] in an investigation of InSb with $n \approx 10^{16}$ cm^{-3}, and it was shown that it is produced at small values of $\omega\tau_p$ and is due to Shubnikov–de Haas oscillations in the sample conductivity. Since the position of the oscillations observed by us did not vary with the pump, we can conclude that the Fermi level in this plasma remained unchanged. Its value was estimated at $\epsilon_F \approx 0.9$ meV, which corresponds to a density $n \approx 5 \times 10^{16}$ cm^{-3}.

Thus, investigations of the absorption and of the dispersion show that at $I > I_{thr}$ the density of an electron-hole plasma does not increase monotonically; the plasma seens to become laminated in the excitation region into dense and rarefied phases.

An investigation of the dependence of the intensity of the recombination radiation on the excitation power has show that an emission line of the "ordinary" exciton condensate (0.709 eV) is produced in thin samples ($\lesssim 50\ \mu$) simultaneously with the appearance of the threshold phenomena at microwave frequencies. When the temperature wave varied, the threshold point shifted little and followed the threshold in the microwave phenomena. In bulky samples (thickness > 200 μ), the radiation threshold coincided with the microwave threshold at $T > 3\,^\circ$K, but at $T < 3\,^\circ$K the radiation threshold shifted abruptly into the region of weak pumping, in analogy with [5], whereas in the microwave phenomena there were no substantial changes. Thus, the conditions for the appearance of the above-mentioned plasma regions (namely: appreciable threshold pumping, weak dependence of the threshold of the phenomenon on the temperature), and also the properties of this plasma (its density and τ_p) differ appreciably from the properties and the threshold conditions for the appearance of a condensed phase of excitons. [5,6] In [1,2], where germanium samples were pulse-excited, the results obtained were similar to those described above, namely, at sufficiently large pumping ($\bar{n} > 10^{15}$ cm^{-3}), after the end of the exciting pulse, a threshold-dependent absorption of microwave radiation appeared, in the form of irregular fluctuating bursts, this indicating that the absorption is due to the appearance of dense-plasma regions. It has turned out, however, that these plasma bunches exist in the sample for a time not exceeding < 10 μsec, whereas the recombination radiation was attenuated with a time constant > 30 μsec.

In our opinion, the described results can be explained by assuming that a phase transition takes place in the nonequilibrium EHP in a sample layer near its surface, i. e., the plasma becomes stratified into a "plasma vapor" and a "plasma liquid." The state of the "plasma liquid," as follows from the plasma measurements, seems to be metastable, and the plasma relaxes rapidly into "ordinary" drops of exciton condensate. In the case of surface excitation of the samples, electrons and holes are generated on the surface, and diffuse into the interior of the sample, where they are bound into excitons. In a layer ~3 μ thick near the surface, the concentration of the unbound free carriers turns out to be quite appreciable, and its value depends little on the sample temperature. Estimates show that at $I \approx 5 \times 10^{19}$ cm^{-2} sec^{-1} the density of the EHP near the surface (at a distance 30 μ) can reach 10^{14} cm^{-3}. At $T < 10\,^\circ$K such a plasma is ideal, and a plasma phase transition is expected to occur in it. [7]

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