of a photon Bose condensate. To be sure, the maximum value δ_{max} of the imaginary part turns out to be of the order of $b^{1/2}\omega_0$, i.e., much smaller than the value ω_0 (see (13)) of the imaginary part that characterizes the system instability in the absence of the photon Bose condensate. Therefore the state investigated in Sec. 2 can be stable in the presence in the system of a damping ν much smaller than ω_0 but larger than δ_{max}. Then, to the extent that $\nu/\omega_0 \ll 1$ is small, the results of Sec. 2 remain practically unchanged. If, however, $\nu \ll \delta_{max}$, then a multimode generation regime will be realized in the system, and the results of Sec. 2 will be unsuitable in this case.

The authors thank B. A. Volkov and V. F. Elesin for useful remarks and for discussions of the results.

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Effect of electron-hole drop size in germanium on the absorption and scattering of radiation in the far infrared region of the spectrum

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The principal optical characteristics of an EHD in the long-wave IR region is investigated theoretically and experimentally for drops of increasing size. The spectral dependences of the light-pressure and radiation extinction, absorption, and scattering coefficients, as well as the radiation scattering indicatrices have been calculated with the aid of a computer in the framework of the general Mie theory for radiation in the 40–1200-μ region and EHD of different radii in the 0.5–500-μ range. A shift of the spectra toward the region of longer waves as the EHD size increases and the excitation level is raised is theoretically predicted and experimentally confirmed. On the basis of these data, the values of the EHD radius, r, are determined, and it is concluded that the size distribution of the drops at a temperature of 1.5–2.0 K in germanium is characterized by an $r^{-\nu}$-type function (Young's distribution) truncated at $r \leq r_{min} = 1$ and $r \geq r_{max} = 16\ \mu$, $\nu = 3$–4. It is shown that larger-sized EHD are formed in germanium doped with shallow impurities. The phenomenon of mutual repulsion between the electron-hole drops and the phonon wind was observed in the experiments at elevated excitation levels and mean nonequilibrium-carrier concentrations higher than 10^{15} cm^{-3}. From these data the averaged characteristics of the phonons effectively interacting with the EHD in germanium are estimated.

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I. INTRODUCTION

The discovery of the phenomenon of resonance absorption of long-wave IR radiation by electron-hole drops (EHD) in germanium[1] marked the beginning of the investigation of exciton condensation and the properties of EHD in the far IR and the submillimeter regions of the spectrum. As a result of the development of the theory of plasma resonance in EHD under the assumption that the EHD dimensions are small compared to the radiation wavelength and with allowance for the intraband and interband electron transitions in the crystal,[2]

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the experimental resonance-absorption spectra of EHD in germanium have been satisfactorily accounted for in the entire investigated photon-energy range of 1–30 meV. [2] From a comparison of the theory with experiment a number of important EHD parameters in germanium were determined and the frequency dependence of the complex permittivity of the EHD material in a broad region of the spectrum was established. [2]

The information obtained as a result of these investigations about the properties of the electron-hole liquid in germanium allows us, in principle, to study the principal optical characteristics of EHD in the indicated spectral region, and not only for small drops, but also in the more general case of EHD of arbitrary dimension. Such an analysis should evidently be based on a more general theory, not limited by the condition of smallness of the particle dimensions in comparison with the radiation wavelength. Highly desirable, of course, is the possibility of a comparison of the data obtained from the general theory with the results of the experimental investigation of the EHD in the longwave IR region under conditions when the EHD dimensions cease to be small as compared to the radiation wavelength. Besides the general interest connected with the study of the changes in the optical characteristics of EHD as they increase in size, such an analysis is also important from the standpoint of the determination of the limits of applicability of the earlier-used electric-dipole approximation, which makes possible the interpretation of the spectra of EHD both under normal conditions and, in particular, under conditions when the system is acted upon by external influences such as magnetic fields, uniaxial strains in the crystals, etc.

The present paper is devoted to these questions, to wit, to the theoretical and experimental study of the effect of drop size on the optical properties of EHD in pure and doped germanium in the long-wave IR region.

II. EXPERIMENTAL SPECTRA OF LONG-WAVE IR RADIATION ATTENUATION BY ELECTRON-HOLE DROPS IN GERMANIUM

1. *Distinctive features of the experimental procedure.* In the present work we measured the transmission spectra of germanium in the 40–1200-μ far IR region under conditions of optical excitation of nonequilibrium current carriers in the crystal. The experimental procedure was similar to the one previously described in Ref. 1. The experimental materials were located directly in liquid helium at a temperature of 1.6 K.

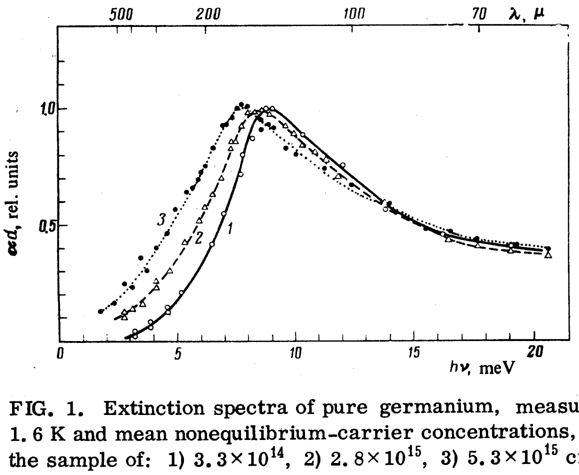

FIG. 1. Extinction spectra of pure germanium, measured at 1.6 K and mean nonequilibrium-carrier concentrations, $\bar{n}$, in the sample of: 1) 3.3×10^{14}, 2) 2.8×10^{15}, 3) 5.3×10^{15} cm^{-3}.

With the object of producing drops of larger dimensions in contrast to the earlier investigations, the excitation density of the crystal was significantly raised primarily by using samples of small area and thickness. Radiation from a hundred-watt incandescent lamp, as well as a probing long-wave IR radiation flux from a diffraction spectrometer, was focused by conical light conductors in the cryostat on a spot of diameter 3.5 mm on the surface of the sample. The maximum flux density of the exciting radiation was then 1 W/cm^2. As will be shown below, a very important circumstance for the production of sufficiently high mean carrier concentrations, $\bar{n} > 10^{15}$ cm^{-3}, in the sample turned out to be the condition that the transverse dimensions of the sample be not greater than the dimensions of the exciting-light spot ("bounded" samples). In measurements on larger-sized samples the attainment of mean carrier concentrations exceeding 10^{15} cm^{-3} turned out to be difficult. The investigations were carried out on crystals of pure germanium ($N_{imp} \sim 10^{12}$ cm^{-3}) and on germanium crystals doped with shallow donors ($N_d \leqslant 7\times10^{15}$ cm^{-3}), the conditions for condensation in which were, apparently, substantially different.

2. *Experimental results.* The experimental spectra measured at an exciting-radiation density of 1 W/cm^2, and evaluated, as usual, [1] in terms of the magnitude of the optically induced attenuation, αd, are shown in Fig. 1 for two "bounded" pure-germanium samples of diameter 3.5 mm and thicknesses 0.1 and 0.06 mm (the curves 2 and 3 respectively). We show in the same figure for comparison the spectrum (the curve 1) measured on a sample of thickness 0.4 mm at a significantly lower excitation density ~0.1 W/cm^2, which is typical of the earlier experiments. [1,2] For convenience of comparison, the spectra have been normalized to unity by the magnitude of the attenuation at the maximum $(\alpha d)_{max}$ = 0.59 (1), 0.95 (2), and 0.73 (3).

As follows from Fig. 1, with increase of the excitation density and, consequently, of the mean concentration of the carriers that have condensed into EHD the maximum and long-wave edge of the extinction spectrum shift toward the region of longer wavelengths. This spectral shift is observable at mean carrier concentrations $\bar{n} \geqslant (5-7)\times10^{14}$ cm^{-3}. At lower $\bar{n}$, as the experiments showed, the position and shape of the extinction spectra remain unchanged.

As was shown in our previous investigations, [1] as well as in some subsequent works, [3] similar changes in the extinction spectra of EHD are observable also in samples of germanium doped with small impurities. Even at relatively low excitation densities (~0.1 W/cm^2), as the impurity concentration is increased, there are observed a change in the shape of the spectra and a shift of them toward the region of longer wavelengths.

III. COMPUTATION OF THE OPTICAL CHARACTERISTICS OF EHD IN GERMANIUM IN THE LONG-WAVE IR REGION ON THE BASIS OF THE GENERAL MIE THEORY

The theoretical study of the optical characteristics of EHD in germanium is carried out in the present paper within the framework of the general theory of the interaction of electromagnetic radiation with spherical particles of arbitrary radius (Mie's theory[4-6]). It is assumed that the particles are homogeneous, and that the scattering of the radiation by neighboring particles occurs incoherently.

1. *Method of computation.* The perturbation introduced by the EHD into the electromagnetic-wave field is determined by both the deviation of the optical properties of a drop from the properties of the surrounding medium and the relative dimensions of the drop as compared to the wavelength of the radiation. It is convenient to characterize each of these circumstances by an appropriate dimensionless parameter:

$$m=\frac{m_c}{m_0},\quad \rho=\frac{2\pi r}{\lambda_0}=\frac{2\pi r}{\lambda}m_0, \tag{1}$$

where m_c is the complex refractive index of the material of the EHD, m_0 is the refractive index of the medium (germanium), r is the drop radius, and λ and λ_0 are the wavelengths in a vacuum and in the medium.

Within the framework of the general Mie theory, which is based on the rigorous solution of the problem of the diffraction of a plane monochromatic wave by a spherical particle, the optical characteristics of a particle are determined in the form of uniformly convergent series in terms of the partial waves of the diffracted radiation. In the present work we computed the following optical characteristics of an EHD with radius r:

a) the extinction cross section

$$\sigma_e(r,\lambda)=\pi r^2\frac{2}{\rho^2}\sum_{l=1}^{\infty}(2l+1)\,\mathrm{Re}\,(a_l+b_l)=\sigma_e^*(r,\lambda)\pi r^2, \tag{2}$$

where $\sigma_e^*(r,\lambda)$ is the dimensionless extinction cross section; b) the scattering cross section

$$\sigma_s(r,\lambda)=\pi r^2\frac{2}{\rho^2}\sum_{l=1}^{\infty}(2l+1)\,(|a_l|^2+|b_l|^2)=\sigma_s^*(r,\lambda)\pi r^2; \tag{3}$$

c) the absorption cross section

$$\sigma_a(r,\lambda)=\sigma_e(r,\lambda)-\sigma_s(r,\lambda); \tag{4}$$

d) the intensity of the radiation scattered by a drop in a given direction:

$$I(r,\lambda,m,\beta)=\frac{\lambda^2}{4\pi^2}\sum_{l=1}^{\infty}\frac{2l+1}{l(l+1)}\{a_l(\rho,m)\pi_l(\beta)+b_l(\rho,m)\tau_l(\beta)\}, \tag{5}$$

where $\pi_l(\beta)$ and $\tau_l(\beta)$ are functions depending only on the scattering angle β[5,6];

e) the light-pressure coefficient, which characterizes the magnitude of the momentum transferred to the drop by the radiation incident on it:

$$\sigma_p(r,\lambda)=\sigma_e(r,\lambda)-\sigma_s(r,\lambda)\,\overline{\cos\beta},$$

$$\overline{\cos\beta}=\frac{4}{\rho^2}\sum_{l=1}^{\infty}\left\{\frac{l(l+2)}{l+1}\mathrm{Re}\,(a_la_{l+1}^*+b_lb_{l+1}^*)+\frac{2l+1}{l(l+1)}\mathrm{Re}\,(a_lb_l^*)\right\}. \tag{6}$$

In this case the force (the "propelling momentum") transmitted to the drop by radiation of intensity $P(\lambda)$ incident on it is equal to

$$F(r,\lambda)=\frac{1}{c}P(\lambda)\sigma_p(r,\lambda), \tag{7}$$

where c is the velocity of light.

Thus, the problem reduces to that of computing the coefficients a_l and b_l, which determine the amplitudes of the electric and magnetic parts of the partial waves (l is the wave index), and of evaluating the sums (2)–(6). In the Mie theory the amplitude coefficients a_l and b_l are usually represented in the form of two particular Bessel functions.[4-6] In the present work we used the more convenient—for computer calculations—expressions[7]:

$$a_l(m,\rho)=\frac{[A_l(m,\rho)/m+l/\rho]\mathrm{Re}\{W_l(\rho)\}-\mathrm{Re}\{W_{l-1}(\rho)\}}{[A_l(m,\rho)/m+l/\rho]W_l(\rho)-W_{l-1}(\rho)},$$
$$b_l(m,\rho)=\frac{[mA_l(m,\rho)+l/\rho]\mathrm{Re}\{W_l(\rho)\}-\mathrm{Re}\{W_{l-1}(\rho)\}}{[mA_l(m,\rho)+l/\rho]W_l(\rho)-W_{l-1}(\rho)}, \tag{8}$$

where $A_l(x)$ and $W_l(x)$ are certain functions (in general, complex) expressible in terms of the spherical Bessel functions $\Psi_l(x)$:

$$A_l(x)=\frac{\Psi_l'(x)}{\Psi_l(x)},\quad W_l(x)=\Psi_l(x)+(-1)^l\Psi_{-l}(x). \tag{9}$$

The spectral dependences of the absorption, scattering, and extinction cross sections and of the light-pressure coefficient, as well as the indicatrices of the radiation scattered by the drops, were calculated numerically on a computer, using the above-presented formulas on the basis of the data, obtained earlier by us, on the spectral dependence of the complex refractive index, $m(\lambda)$, of the material of the EHD in the long-wave IR region.[2] The optical characteristics of the EHD were computed in the spectral region $h\nu=1-30$ meV ($\lambda=1240-42\ \mu$) for drop radii $r=0.5-500\ \mu$, which corresponded to the variation of the diffraction parameter ρ within the wide limits from $\rho\ll 1$ (small EHD) to $\rho\gg 1$ (large EHD). Using the data on the particle concentration in an EHD, $n_c=2\times 10^{17}$ cm^{-3} (without allowance for the mass renormalization[2]), we can easily estimate the cross section per electron-hole pair in the EHD:

$$\sigma^{eh}(\lambda)=\frac{\sigma(\lambda)}{{}^4/_3\pi r^3 n_c}, \tag{10}$$

and from the experimentally measured absorption coefficient $\alpha(\lambda)=\sigma(r,\lambda)N(r)$, where $N(r)$ is the number of drops in a unit volume of the crystal, determine the average—over the sample—nonequilibrium carrier concentration in the condensed phase:

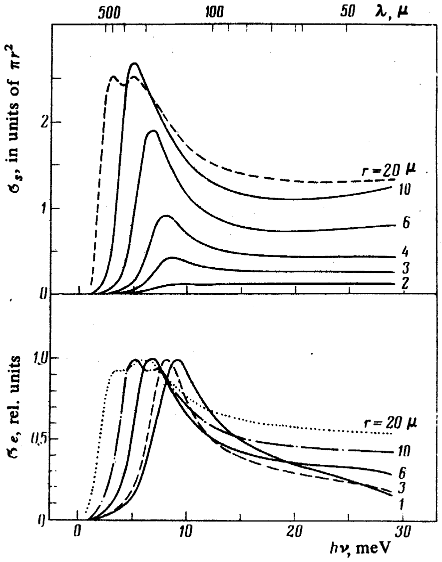

FIG. 2. Values of the extinction, (2), and scattering, (3), cross sections computed with the aid of the general Mie theory for EHD of different radii r. The extinction cross section data have been normalized to unity; the absolute values of these cross sections at the peaks of the spectra are given in Fig. 3.

$$\bar{n}=\alpha(\lambda)/\sigma^{eh}(\lambda). \tag{11}$$

2. *The results of the computation.* The results of the numerical computation of the spectral dependences of the extinction and scattering cross sections from the formulas (2) and (3) for EHD of different sizes are presented in Fig. 2. The extinction spectra have, for convenience of comparison, been normalized to unity with the extinction value at the peak. The absorption spectra of the EHD are not shown here since they virtually coincide in shape and position with the corresponding extinction curves in Fig. 2 (the absolute absorption cross-section values at the peaks are shown in Fig. 3).

As follows from the above-presented computations, the extinction spectra remain unchanged in shape and position for all particles with radius $r \leqslant 1$ μ and virtually coincide with the computed absorption spectra. In other words, the scattering of the radiation in this case is negligibly small. The comparison of these spectra with the spectra computed in the electric-dipole approximation[2] reveals total identity of the spectra, and substantiates the applicability of the electric-dipole model in the description of the absorption spectra of EHD with $r \leqslant 1$ μ.

As can be seen from Fig. 2, as r increases from 1 to 20 μ, the computed extinction and scattering (and absorption) spectra shift in like manner toward the region of lower photon energies. For large EHD with $r \geqslant 50$ μ, the spectra lose the resonance shape, and the extinction cross section, σ_e, tends to the value $2\pi r^2$, which corresponds to the $\rho \gg 1$ diffraction limit.[5,6] Figure 3 shows the absolute values of the extinction, scattering, and absorption cross sections at the peaks of the curves for the EHD as functions of the EHD radius. It can be seen that the fraction of the radiation that can be scattered by a drop becomes commensurate with the losses due to absorption only for EHD with $r \geqslant 4-7$ μ. It can be seen from the same figure that long-wave IR radiation is attenuated (absorbed) most effectively—judging from the attenuation (absorption) per electron-hole pair —by drops of small radius ($r < 2$ μ), for which $\sigma_e^{eh}(\max) = \sigma_a^{eh}(\max) = 4.4 \times 10^{-14}$ cm^2.

The results of the computation from (5) of the angular diagrams of the scattered-radiation intensity for some of the most typical cases are presented in Fig. 4. It can be seen from the figure that the polar diagram stretches out in the forward direction as the relative EHD size increases in the case when $\rho \geqslant 1$.

According to the calculations of the light-pressure coefficient, σ_p, from (6), the magnitude and spectral dependence of this quantity virtually completely coincide with the corresponding data for the extinction cross section σ_e. Consequently, the most effective—in the sense of the transfer of the momentum of the incident photons

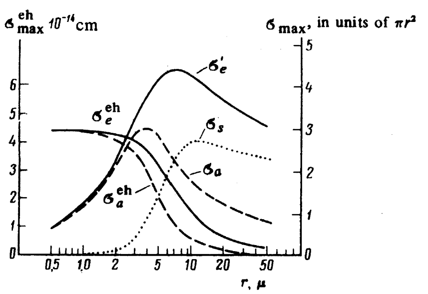

FIG. 3. Computed values of the maximum—in the frequency dependences—cross sections for extinction, σ_e, absorption, σ_a, and scattering, σ_s, as well as of the corresponding cross sections, σ^{eh}, per electron-role pair in an EHD, , as a function of the drop radius (the σ^{eh}_{max} are given in units of 10^{-14} cm^2).

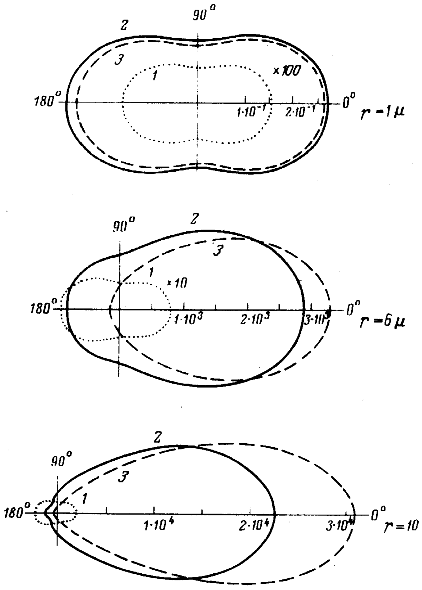

FIG. 4. Scattering indicatrices computed for drops of radii r = 1, 6, and 10 μ at three characteristic points of the spectrum: 1) 3 meV (410 μ), 2) 9 meV (138 μ), 3) 15 meV (83 μ).

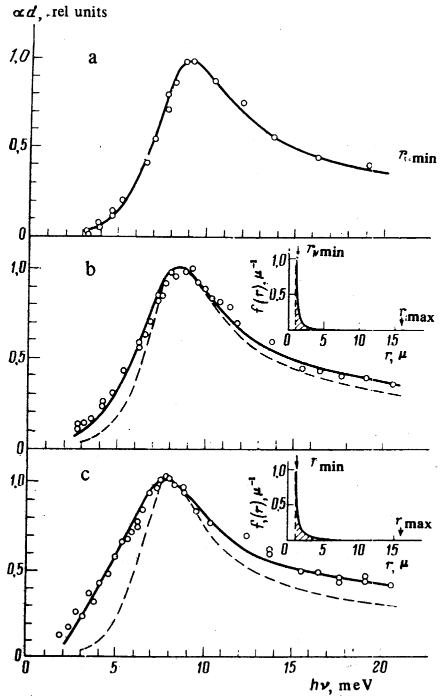

FIG. 5. Extinction spectra of EHD in pure germanium at three excitation levels corresponding to mean carrier concentrations, $\bar{n}$, in the sample of: a) 3.3×10^{14} cm^{-3} ($\alpha d_{max}=0.59$), b) 2.8×10^{15} cm^{-3} ($\alpha d_{max}=0.95$), c) 5.3×10^{15} cm^{-3} ($\alpha d_{max}=0.73$). The points represent the experimental data. The curves represent the results of the general-Mie-theory calculations. The dashed curves are for a monodisperse system of EHD with radii: a) $r\leqslant1$, b) $r=2$, c) $r=3\,\mu$; the continuous curves, for a polydisperse system of EHD with a size distribution of the drops of the type of the Young distribution (12) with the parameters $r_{min}=1\,\mu$, $r_{max}=16\,\mu$, $\nu=4$ (5,b), and $\nu=3$ (5,c). The distribution functions, $f(r)$, for these parameters are shown on the right of the figure.

to the EHD—frequency region is the region of the plasma frequencies of the EHD.

IV. COMPARISON OF THE THEORY WITH EXPERIMENT. DISCUSSION OF THE RESULTS

1. *The extinction spectra in pure germanium. The size distribution of the EHD.* As the experimental investigations in the far IR region in pure germanium at $T<2$ K showed, the position and shape of the extinction spectra of the EHD remain unchanged for all nonequilibrium-carrier concentrations $\bar{n}<(5-7)\times10^{14}$ cm^3. These spectra are well described by the approximate theory of electric-dipole absorption of radiation by EHD of small dimensions, i.e., by EHD for which $\rho\ll1$.[2] On the other hand, the exact computation based on the general Mie theory yields a similar result for the spectra of EHD if the drop dimensions do not exceed 1 μ (Fig. 5a). Thus, we can conclude that, under the indicated type of conditions[1,2] the condensed electron-hole phase is formed in the form of EHD whose dimensions do not exceed 1 μ.

As has already been noted, for mean nonequilibrium carrier concentrations in the sample $\bar{n}\geqslant10^{15}$ cm^{-3} there is observed, as the excitation level is raised, a shift of the experimental extinction spectra toward the region of longer wavelengths. This shift agrees with the shift of the theoretical spectra as the EHD radius increases in the case when $r>1\,\mu$ (Fig. 5), and indicates that the drop dimension increases with increasing $\bar{n}$.

At the same time it can be seen from Fig. 5, b) and c) that the computed spectra nevertheless differ appreciably from the experimentally measured spectra in their shapes. The next natural step in the description of the extinction spectra of EHD was the introduction of the size distribution of the drops into the theory. Various distribution functions, $f(r)$, that are the most typical of dispersed media were tested: the normal Gaussian distribution, the gamma distribution, and Young's distribution.[7,8] The absorption coefficient $\alpha(\lambda)$ in this poly-disperse case was defined in the form

$$\alpha(\lambda)=\int_0^\infty\sigma(r,\lambda)f(r)\,dr.$$

As was to be expected, the introduction of the distribution function led to the broadening of the theoretical spectra and an improvement in their agreement with the experimental data. The most satisfactory agreement between the theory and experiment was obtained with the Young distribution:

$$f(r)=\begin{cases}0 & r<r_{min},\ r>r_{max}\\ \dfrac{N(\nu-1)r_{min}^{\nu-1}}{1-(r_{min}/r_{max})^{\nu-1}}r^{-\nu} & r_{min}\leqslant r\leqslant r_{max}\end{cases}\qquad(12)$$

As can be seen from (12), this distribution is essentially nonsymmetric, and has the character of a decreasing power function, $r^{-\nu}$, truncated on the small- and large-radius sides. Evidently, there cannot exist in an EHD system drops with dimensions smaller than some critical dimension, determined by the condition of thermodynamic stability of the nucleus of the liquid phase.[9] On the other hand, according to the theoretical and experimental investigations published in Refs. 9 and 10, there also exists a certain maximal critical EHD dimension determinable with allowance for the phonon wind from the EHD. Thus, the use of such a limited distribution is physically justified. The best agreement between the computed and measured spectra in Fig. 5 was obtained for $f(r)$ with the parameters $r_{min}=1\,\mu$, $r_{max}=16\,\mu$, and $\nu=4$ (the curve in Fig. 5b), or $\nu=3$ (the curve in Fig. 5c). We should dwell on the question how accurately these parameters have been determined. According to our calculations, the shape of the spectra virtually does not depend on the EHD dimensions for drops with $r<1\,\mu$. At the same time the computed spectra turn out to be quite sensitive to the choice of the quantity r_{max}. The calculations were carried out for different values of r_{max}. The best agreement with experiment was obtained with $r_{max}=14-18\,\mu$. This quantity agrees satisfactorily with other estimates.[9,10] It should be noted that in all our calculations we assumed that the damping of the plasma oscillations is determined by the electron-hole collisions, and does not depend on the EHD dimensions.

Using the obtained data, we can estimate certain mean quantities, $\bar{\sigma}^{eh}(\lambda)$ and $\bar{n}$, for the polydisperse EHD system, [11] quantities which, under the conditions of the experiments (Fig. 5, a, b, and c), turned out to be respectively equal to:

a) $\bar{\sigma}_e^{eh}(\max) = 4.4\cdot10^{-14}\text{cm}^2, \bar{n} = 3.3\cdot10^{14}\text{ cm}^{-3}$,

b) $\bar{\sigma}_e^{eh}(\max) = 3.4\cdot10^{-14}\text{cm}^2, \bar{n} = 2.8\cdot10^{15}\text{ cm}^{-3}$,

c) $\bar{\sigma}_e^{eh}(\max) = 2.3\cdot10^{-14}\text{cm}^2, \bar{n} = 5.3\cdot10^{15}\text{ cm}^{-3}$,

Thus, it follows from a comparison of the experimental spectra with the results of the calculation of the attenuation by EHD by means of the general theory with allowance for the size distribution of the drops that, as the mean concentration of the electrons and holes in the sample increases, the mean EHD dimension increases, this increase being first and foremost due to an increase in the fraction of large drops. This result agrees with the data obtained in other investigations. [12-14] At the same time the size distribution of the drops given in the present paper and its variation with $\bar{n}$ differ appreciably from the results obtained in Refs. 13 and 15. Possibly, this is explained by the fact that the data of Refs. 13 and 15 do not take into account the variation of the sensitivity of the method with respect to drops of different dimensions, and, moreover, they pertain to a region of the crystal far from the excitation point.

2. *The extinction spectra in doped germanium.* As has already been noted, a substantial shift of the extinction spectra of the EHD toward the region of longer wavelengths was registered in the investigation of doped-germanium crystals as the donor concentration was increased to $(3-7)\times10^{15}$ cm^{-3}. [1,3] By their nature, these changes correspond to the changes observed in experiments at elevated excitation levels of the crystal, and can, in principle, be explained by increases in the drop dimensions in the doped crystals. As can be seen from Fig. 6, the results of the spectral measurements on n-type germanium ($N_{As} = 7\times10^{15}$ cm^{-3}) are satisfactorily described by the curves computed in the monodisperse approximation for EHD of radius 10 – 20 μ.

Generally speaking, there can occur in doped crystals during their optical excitation a number of phenomena that compete with the drop absorption. Such effects may, for example, be due to the presence of compensated impurities in the sample, [1] the formation of H^- centers [16,17] the production in the crystal of free and bound excitons. [14,18] Apart from the fact that all these effects are

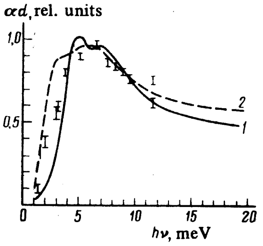

FIG. 6. Extinction spectra computed with the aid of the general Mie theory foo a monodisperse system of EHD with radii $r = 10$ (the curve 1) and 20 μ (the curve 2). The points represent experimental data obtained for germanium doped with arsenic ($N_{As} = 7\times10^{15}$ cm^{-3}).

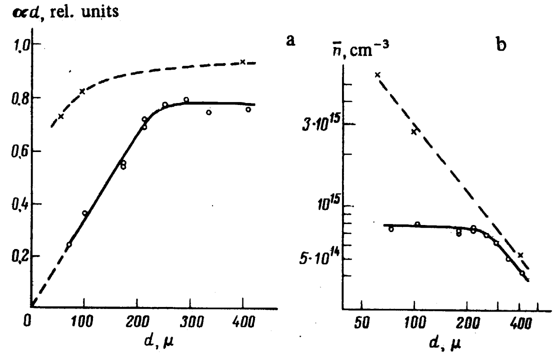

FIG. 7. Dependence of the attenuation magnitude at the curve peak, (a), and of the mean charge-carrier concentration in an EHD, (b), on the crystal thickness for a wedge-shaped (continouus curves) and bounded (dashed curves) germanium samples.

distinguished by a relatively low intensity, they are characterized by dependences (on concentration, type of impurity, etc.) that are substantially different from the dependences observed in the present experiments. [11] Thus, the interpretation offered here of the observed long-wave shift of the extinction curves in doped germanium from the point of view of the formation of larger EHD is quite probable. It agrees with some other data. [13] It is possible that the formation of larger drops in doped germanium is connected with a decrease in the effective thickness of the excitable layer and, consequently, with an increase in the mean nonequilibrium electron-hole concentration in the active region of the crystal.

3. *The repulsion of the electron-hole drops by the phonon wind.* As has already been noted, in the course of the experimental investigation of the optical properties of EHD in the far IR region we discovered an effect which made the production in the sample of high carrier concentrations, i.e., of $\bar{n} > 10^{15}$ cm^{-3}, difficult. All the main investigations in the present work were performed on thin "bounded" samples whose transverse dimensions did not exceed the dimensions of the exciting-light spot. As was to be expected, the mean concentration, $\bar{n}$, of carriers produced by the light in such a sample increased as the sample thickness was decreased right up to $\bar{n} \approx 5\times10^{15}$ cm^{-3}. Here the attenuation almost did not change: $\alpha d = \text{const}$. To achieve the same concentrations in a wedge-shaped sample (with length 25 mm and thickness varying from 500 to 50 μ) turned out to be impossible. As the sample thickness was decreased in the case when $d < 200$–250 μ, the attenuation αd began to decrease linearly (Fig. 7a), while the quantity $\bar{n}$, having attained its limiting value of $\bar{n}_{max} \approx 8\times10^{14}$ cm^{-3}, did not increase further (Fig. 7b).

The effect discovered whereby the mean concentration of the carriers produced in a wedge-shaped sample is limited can be explained within the framework of the theoretical concept of EHD repulsion by the flux of nonequilibrium phonons arising in the process of thermalization and recombination of the charge carriers in the crystal. [19] The observed limiting value $\bar{n}_{max} = 8\times10^{14}$ cm^{-3} agrees with the theoretical estimate ($\bar{n}_{max}^{theor} = 10^{15}$ cm^{-3} [19]), and allows a more accurate determination of the most indeterminate parameter, $(|\mathbf{k}|^4/\omega_k^3) \approx 1.7\times10^{-9}$ $\sec^3/\mathrm{cm}^4$, in the theory. Assuming, as in Ref. 19, that the dominant contribution to the dragging of the EHD is made by the acoustic phonons in the long-lived transverse branches, we obtain $|\mathbf{k}| \approx 4\times10^7\ \mathrm{cm}^{-1}$ and $\overline{\omega}_k \approx 10^{13}$ $\sec^{-1}$, i.e., the phonons that interact most effectively with the EHD turn out to be those in the region of the limiting frequencies of the transverse acoustic phonons. The effective length, estimated from $\bar{n}$, of the extension of the EHD cloud under the action of the phonon wind in the present experiments was ~1 mm.

V. CONCLUSION

The method developed in the present paper for analyzing the optical characteristics of EHD on the basis of the general Mie theory allowed us, firstly, to justify the and determine the limits of its applicability and, secondly, to investigate theoretically with the use of a computer the variation of the principal characteristics of the EHD in germanium as the drop dimensions increase. As has been shown, the shift of the extinction, absorption, and scattering curves toward the longer-wavelength region of the spectrum is the primary effect that occurs as the EHD increase in size. This spectral shift, which can be observed experimentally as the crystal-excitation level is raised, can hardly be justified by simple qualitative arguments, and is determined first and foremost by the nature of the frequency dependence of the complex refractive index of the material of the EHD in the spectral region under consideration. It is possible that the growth of the drop dimensions in the experiments in question was due not only to the elevation of the excitation level, but also to some overheating of the sample. It should also be noted that the shift of the spectra was observed under conditions when the drops were repelled by the phonon wind in the sample.

Thus far, we have not taken into consideration the interference of the radiation scattered by neighboring drops. This is permissible if the mean distance between the drops is much greater than the wavelength, λ_0, of the radiation in the medium (in germanium). It can be shown that, under our conditions, the decrease in the measurable extinction coefficient due to the effect of the coherent scattering constitutes roughly 5%, i.e., is insignificant.[11]

The computations carried out in the present work of the spectral dependence of the light-pressure coefficient allow the delimitation of the experimental possibilities of the observation of the motion of the EHD under the action of the photon pressure. The most effective in this respect is the frequency region near the plasma resonance in the EHD, $h\nu \approx 9$ meV (Fig. 2). It is not difficult to estimate with allowance for (7) and (10), as well as for the data on σ_p, the radiation intensity in this spectral range that is necessary for the displacement of the EHD over the experimentally observed distances L:

$$P(\lambda)=\frac{c(m_e+m_h)}{\tau_r\tau_0}\frac{L}{\sigma_p^{\mathrm{eh}}(\lambda)}. \qquad (13)$$

The effect of EHD dragging by the photon flux is maximal for drops of small dimension ($r \leqslant 1\ \mu$), which are characterized by the greatest $\sigma_p^{\mathrm{eh}}(\max) = 4.4\times10^{-14}\ \mathrm{cm}^2$. Setting $\tau_0 = 4\times10^{-5}$ sec, $m_e + m_h = 0.4m_0$, $L = 0.1$ cm, and the drop-momentum relaxation time $\tau_r \approx 10^{-7}$ sec, we obtain that, in the region of wavelengths $\lambda \sim 150\ \mu$ ($h\nu \sim 9$ meV), a radiation-flux density $P \sim 1\ \mathrm{W/cm}^2$ is necessary for this purpose. Such powers can, in principle, be attained with the aid of present-day submillimeter lasers.

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