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Electron–hole drop radiation in the far infrared part of the spectrum

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It was established experimentally that the effects attributed earlier to electron–hole drops in the far infrared may, in fact, be due to the room-temperature background radiation modulated by resonant absorption in the drops.

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Vavilov, Zayats, and Murzin[1,2] reported the discovery of resonant emission of submillimeter radiation at the plasma frequency of electron–hole drops in germanium. To explain the physical nature of this effect, we proposed[3] a mechanism of the excitation of plasma oscillations by fast Auger electrons resulting from carrier recombination in electron–hole drops. Further detailed investigations were desirable to determine the role of this mechanism. However, our attempts to observe drop radiation were unsuccessful although it was reported by Zayats[2] that the integrated intensity of the radiation amounted to 10^{-7} W/cm^2. In the present paper we shall give experimental evidence suggesting that the phenomenon discovered by Vavilov *et al.*[1,2] could be due not to the emission but to resonant absorption of the room-temperature background radiation by the drops.

In the first series of experiments we recorded submillimeter radiation using a photoresistor made of silicon doped with boron in a concentration of $\approx 5\times 10^{14}$ cm^{-3}. At helium temperatures and under the action of impurity-absorbed illumination of wavelength shorter than 30μ the optical charging of neutral boron atoms in silicon produced the A^+ centers with an ionization energy of about 3 meV (the spectral range of the detector extended to 500μ, with a sensitivity maximum at 300μ [4]). The threshold sensitivity of our device in the 100–400μ range was at least 5×10^{-13} W/Hz$^{1/2}$ at 1.6 °K. Under the experimental conditions (Fig. 1) the source of the impurity-absorbed illumination necessary for the operation of the detector 1 was the room-temperature background radiation 5 which passed along a stainless-steel tube 2. Samples of pure (with an impurity concentration $N\approx 10^{11}$ cm^{-3}) and doped ($N\approx 5\times 10^{14}$ cm^{-3}) germanium 4 were excited with modulated radiation from an argon laser 6 whose power was up to 150 mW and which was focused on a sample in the form of a spot ≈ 5 mm in diameter. The formation of drops in the samples was deduced from the recombination radiation (luminescence) spectrum. The photodetector was protected from the exciting and recombination radiations by a filter 3 made of indium antimonide, 2 mm thick, and black polyethylene. The experiments were carried out at temperatures below 2.1 °K. Two relative positions of the germanium sample and photodetector were tried. In the first case (Fig. 1a) the background radiation passed first through the photodetector and then through the germanium plate. Under these conditions we observed no photoresponse from the detector even at the highest rate of excitation of germanium. Since under our conditions the sensitivity of the photodetector to submillimeter radiation was at least as high as in the work of Vavilov *et al.*,[1,2] we concluded that the long-wavelength radiation emitted from drops in germanium could hardly have been discovered by Vavilov *et al.*[1,2] In the second case (Fig. 1b, when the background radiation first passed through germanium and then through the photodetector, we recorded a photoresponse which was approximately three orders of magnitude higher than

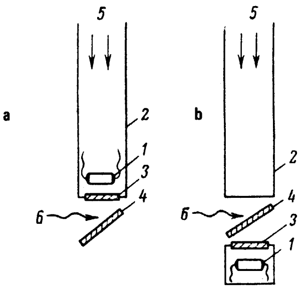

FIG. 1. Schematic diagrams of the experimental set ups employing a boron-doped silicon detector: 1) photodetector; 2) stainless-steel tube; 3) filter made of indium antimonide and black polyethylene; 4) germanium sample; 5) background radiation; 6) exciting radiation.

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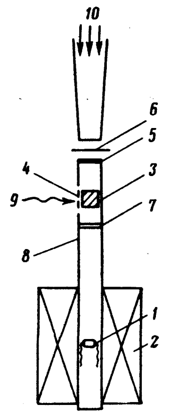

FIG. 2. Schematic diagram of the experimental set up using a detector made of *n*-type indium antimonide tuned by a magnetic field: 1) photodetector; 2) superconducting solenoid; 3) germanium sample; 4) metal grid; 5) metal screen; 6) movable metal screen; 7) filter made of black polyethylene. 8) polished copper tube; 9) exciting radiation; 10) background radiation.

the noise for an excitation power of about 80 mW. A strong photoresponse in the submillimeter region reported by Zayats[2] was obtained when the apparatus was arranged as in Fig. 1b. In fact, in the experiments reported by Vavilov *et al.*[1,2] the submillimeter radiation detector (germanium bolometer), placed in a helium bath, was coupled by a light guide to a spectrometer and, therefore, the detector always received the room-temperature background radiation. Thus, the photoresponse of the detector assumed by Vavilov *et al.*[1,2] to represent the submillimeter radiation emitted from drops could, in fact, represent the room-temperature background radiation modulated because of the absorption in the drops.

We carried out a more detailed investigation of the interaction between the drops and the background radiation in a second series of experiments employing a submillimeter radiation detector made of pure indium antimonide, which was tuned by the application of a magnetic field.[5] This detector enabled us to carry out spectral measurements in the submillimeter wavelength range in complete absence of the background radiation. We used the apparatus shown in Fig. 2. A detector 1 was placed in a superconducting solenoid 2 creating magnetic induction *B* up to 5.5 T. A sample of pure germanium 3 ($N \approx 10^{12}$ cm^{-3}) was excited through a metal grid 4 by modulated radiation 9 of wavelength $\lambda = 0.63\mu$ whose power was up to 20 mW or of wavelength $\lambda = 1.06\mu$ whose power was up to 1 W. The grid 4 with $10 \times 10\mu$ mesh was used to protect the measuring channel from possible sources of long-wavelength radiation. The measurements were carried out in the temperature range 1.8–4.2 °K. When the measuring unit was screened completely from the background radiation 10 by the grid 4 and a metal screen 5, there was no response from the detector on photoexcitation of germanium with power up to 1 W and this was true throughout the investigated range of magnetic fields. When the screen 5 was removed, a photoresponse appeared and its magnitude exceeded the noise level by at least an order of magnitude when the excitation intensity was 10 mW and the temperature was 1.9 °K. When the screen 5 was in place but the grid 4 was removed, the photoresponse was approximately five times greater than the noise when the excitation power was ≈1 W. This indicated the need for very careful screening from possible sources of background radiation when measurements were carried out in the submillimeter part of the spectrum by means of high-sensitivity photodetectors.

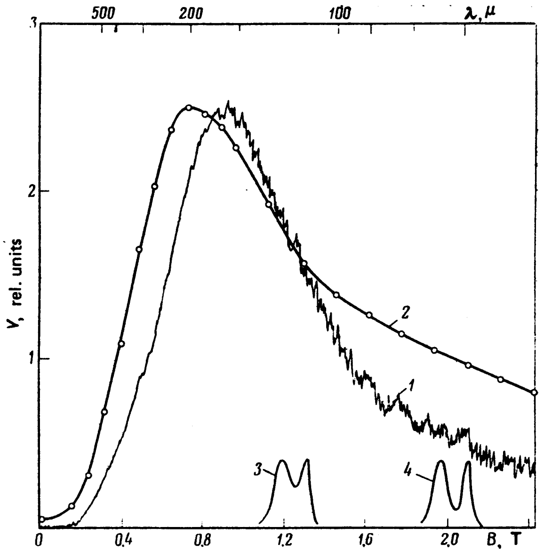

FIG. 3. Photoresponse *V* of an indium antimonide detector plotted as a function of the magnetic induction *B*: 1) photoexcitation of a germanium sample; 2) complete modulation of the background radiation; 3), 4) excitation with submillimeter laser radiation of wavelengths 118.6 and 78.4 μ, respectively.

Figure 3 shows the dependence of the detector photoresponse on the magnetic induction *B* when the background radiation 10 was modulated by the drop absorption and germanium was excited by ≈10 mW with the screen 5 removed. This figure includes also the response of the detector to the background radiation when it was modulated fully and periodically by a cold movable screen 6. The absorption spectrum of the drops could be determined approximately from the results of Fig. 3 by the following method. In strong magnetic fields the photoresponse of our indium antimonide sample was selective (curves 3 and 4 in Fig. 3). Therefore, the detector responded to a fairly narrow part of the background radiation spectrum modulated by the ab-

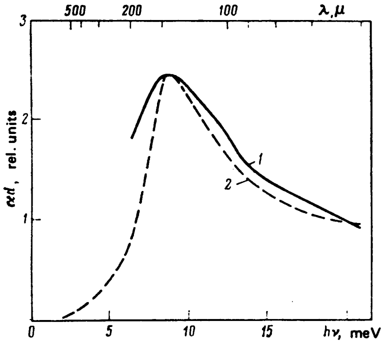

FIG. 4. Spectral distributions of the resonant radiation *αd* of electron—hole drops: 1) results obtained from Fig. 3 by a method described in text; 2) results of Vavilov *et al.*[1,2]

sorption in the drops or by the cold screen. The position of this spectral region was linked directly to the magnetic induction B.[5,6] Thus, the absorption spectrum could be obtained by simple division of the photoresponse obtained as a result of the excitation of germanium by the photoresponse in the case of complete modulation of the background radiation and conversion of the magnetic induction to the photon energy or wavelength, corresponding to the selective sensitivity region at each value of B in accordance with Ref. 6. The spectral dependence of the absorption in the electron—hole drops calculated in this way is plotted in Fig. 4. This figure includes also the absorption spectrum of drops in germanium taken from the papers of Vavilov *et al.*[1,2] It is clear from the figure that the curves are similar although curve 1 was obtained using a cooled detector tuned by a magnetic field and curve 2 using a grating monochromator. In the former case the absorption could be interpreted as the radiation emitted from the electron—hole drops because of the absence of any source of absorbed radiation, apart from the room-temperature background.

We thus failed to observe submillimeter radiation of the electron—hole drops in germanium although we used highly sensitive photodetectors of two different types. Hence, we concluded that the intensity of the long-wavelength drop radiation emitted from germanium (if it existed at all) was several orders of magnitude weaker than that described by Vavilov *et al.*[1,2] However, the room-temperature background radiation passed through an excited germanium crystal and produced a large detector signal with a maximum in the plasma frequency region of the drops. This signal could be erroneously interpreted[1,2] as the radiation emitted from the drops.

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Electric resistance of metals with unfilled *f* shells

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The method of linear response in the paramagnetic phase is used to analyze the resistance of metals with an ϵ_f level of localized f electrons that are located near the Fermi surface. The strong intra-atomic Coulomb repulsion of the f electrons and their hybridization with the s electrons leads, at low temperatures, to the relation $R(T)=R_0+AT^2$, where the residual resistance R_0 of the ideal metal and the sign of A depend on the filling of the f level. It is shown that hybridization scattering accounts for the experimentally observed large logarithmic deviation of $R(T)$ from the linearity called for by the phonon scattering mechanism. In the region of strong hybridization ($|\epsilon_f|/g<1$) at large values of R_0 the resistance can have a minimum. A qualitative comparison of the results of the theory with the experimental $R(T)$ dependence is carried out for a large class of f metals (primarily for metals with variable valence).

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1. It is well known that rare-earth metals,[1-3] actinides,[4] a number of their intermetallic compounds,[5-8] as well as some d-metals[9] have in the paramagnetic phase, both at low and high temperatures, an anomalously varying resistance $R(T)$. At high temperatures, $R(T)$ deviates strongly from linearity, and sometimes even decreases with increasing T, while at low temperatures $R(T)$ can vary either quadratically or have a minimum. This behavior of $R(T)$ is connected with the scattering of the conduction s electrons by the f electrons,[4,10-12] which form either a narrow band near the Fermi surface or a deep level.

If the single-electrons ε_f levels of the unfilled localized-electron shells are much farther from the chemical potential μ than the characteristic energies of the

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