The values of the ionization multiplicity depend on the form of the I(z) curve, which was obtained on the basis of the known experimental data (mainly for Co) and with the aid of the approximation formula of [5]. The results of the numerical solution of (2) yield $\gamma' \approx 1.2$ and $z \approx 25$, in agreement with experiment. The theoretical estimates for other substances lead to values that are higher than the experimental ones. This is possibly due to the possible non-equilibrium of the plasma when $q \gtrsim 10^{12}$ W/cm^2 [6] and to the inaccuracy with which the ionization potentials were approximated.

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RECOMBINATION RADIATION OF THE CONDENSED PHASE OF NONEQUILIBRIUM CARRIERS IN SILICON

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The intense recombination produced in germanium when the threshold excitation level and temperature are reached was investigated in [1, 2]. The main features of this radiation were explained by using a model of a condensate consisting of spherical drops of a degenerate electron-hole plasma [2]. A similar radiation was observed earlier in silicon [3]. The broad maximum of this radiation corresponded to $h\nu = 1.081$ eV and was shifted towards lower energies by 16 meV relative to the main peak of the radiative annihilation of the free excitons, $h\nu = 1.0970$ eV. The occurrence of such a radiation was attributed in [3] to the decay of biexcitons.

We note that the model of a condensate of drops and the biexciton model should lead to essentially different connections between the intensity of the recombination radiation of the free excitons I_e and the intensity of the long-wave radiation. Indeed, the stationary concentration of the biexcitons, n_b, is proportional to the square of the concentration of the free excitons n_e, from which it follows that $I_b \sim I_e$. When the condensate of constant density n is produced at low temperatures, the evaporation of the carriers from the condensed phase can be neglected. The stationary conditions are therefore attained when the flux of free excitons to the exterior surface of the condensate drops, $n_e v\pi r^2$, is equal to the electron-hole recombination rate inside the drop, $(4\pi r^3/3)(n_0/\tau_0)$. Here v is the average thermal velocity of the electrons, r is the radius of the drop, and τ_0 is the lifetime of the condensate. Since the intensity I_c of the recombination radiation of the condensate is proportional to the volume of the condensed phase, and $I_e \sim n_e$, it follows that $I_c \sim I_e^3$. The results that follow lead to just this kind of dependence.

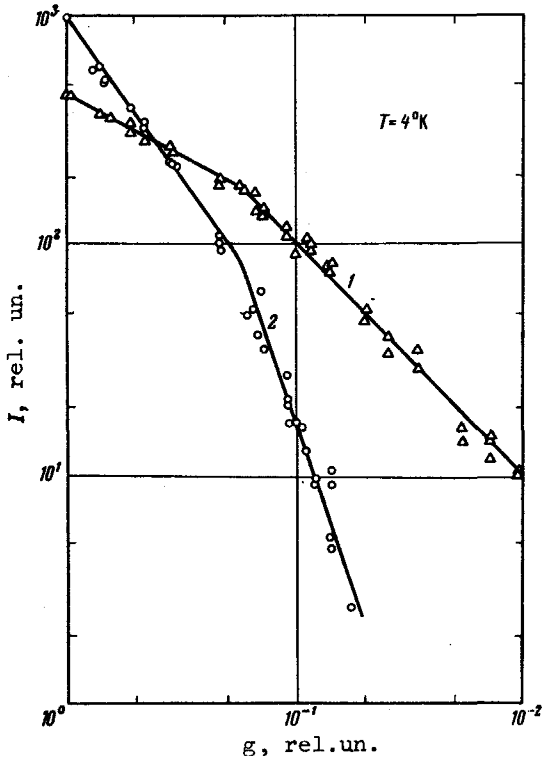

Fig. 1. Radiation intensity I of the free carriers (1) and of the condensed phase (2) vs. the photoexcitation level g in pure silicon.

To excite the recombination radiation, the beam of the cw gallium-arsenide laser of power up to 160 mW was focused on the surface of silicon samples immersed in liquid helium. The exciting-radiation intensity was varied with the aid of calibrated grids. The recombination radiation was modulated with a perforated disc and analyzed with a grating spectrometer (MDR-2). The apparatus made it possible to record spectra with a resolution of ∿0.4 meV. The constancy of the sample temperature was monitored against the constancy of the shape of the free-exciton radiation spectrum.

Figure 1 shows plots of the radiation intensity of the free excitons I_e ($h\nu$ = 1.0970 eV) and of the long-wave radiation I_c ($h\nu$ = 1.0815 eV) against the excitation level. It is seen from the figure that these plots have a complicated character, and I_e and I_c depend linearly and cubically on the intensity of the exciting light only at the minimum excitation level. In all the bands, however, we have $I_c \sim I_e^3$ (Fig. 2). This dependence was well satisfied for all the pure-silicon samples investigated by us.

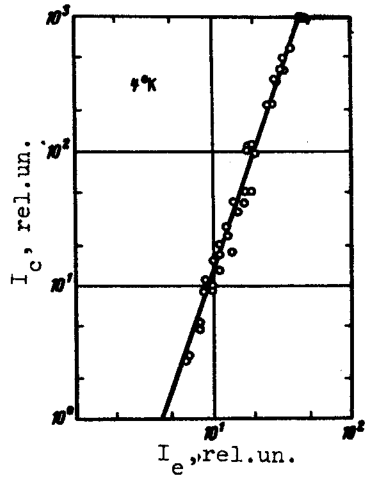

Fig. 2. Radiation intensity I_c of the condensed phase vs. radiation intensity of the free electrons I_e in pure silicon.

The investigation of the dependence of the spectral distribution of the recombination radiation of the excitation level allows us to advance a hypothesis concerning the mechanism whereby the condensate is initiated.

Figure 3 shows the emission spectra of two samples of silicon with different boron contents N_B. At the minimal excitation level, the emission spectrum of the sample with $N_B = 3 \times 10^{14}$ cm^{-3} reveals only a narrow peak with energy $h\nu$ = 1.0924 eV. It was shown in [4] that this emission is produced upon annihilation of the excitons bound to the boron atoms. When the excitation is gradually increased, steps are produced on the long-wave slope of this peak and develop subsequently into peaks with energies 1.0903, 1.0881, and 1.0863 eV. These energies do not correspond to the annihilation peaks of the excitons bound to other group-III or group-V impurity atoms in silicon. At a sufficiently high excitation level, emission of the condensate with a maximum at $h\nu$ = 1.0815 eV appears in the spectrum. We note that the free-exciton emission peak was not observed at all in this material. In the case of silicon having

$N_B = 3 \times 10^{12}$ cm^{-3} at a low excitation level, an analogous structurs is observed against the background of the more intense emission of the free excitons and of the condensate. This structure disappears when the excitation level or the temperature is raised.

Such a successive appearance of narrow peaks with decreasing energies allows us to assume that when the excitation level is increased there can be produced on the impurity atoms complexes containing more than one electron. This leads subsequently to the appearance of the condensate near such complexes. The concentration of the free electrons can still remain slight in this case. Since the emission of these complexes is observed also in relatively pure silicon, it can be assumed that the impurity atoms are the primary condensation centers even if their concentration is low.

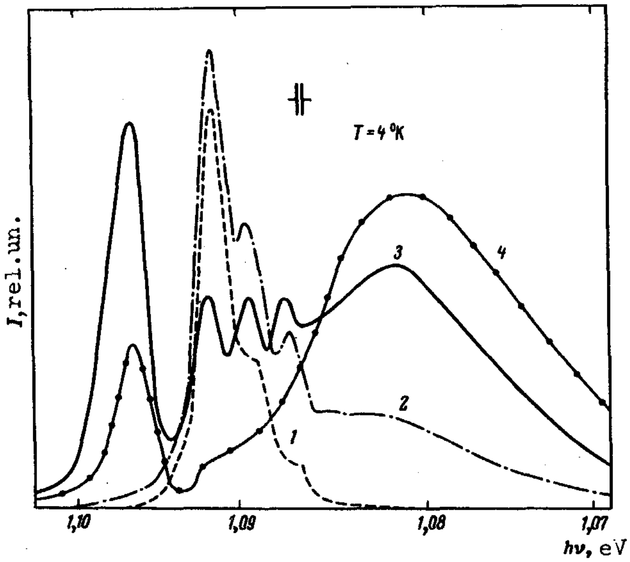

Fig. 3. Spectral distribution of the recombination radiation of silicon at various photoexcitation powers P:
1 - $N_B = 5 \times 10^{14}$ cm^{-3}, P = 40 mW;
2 - $N_B = 5 \times 10^{14}$ cm^{-3}, P = 160 mW;
3 - $N_B = 3 \times 10^{12}$ cm^{-3}, P = 50 mW;
4 - $N_B = 3 \times 10^{12}$ cm^{-3}, P = 160 mW.

The concentration of the electrons and holes in the condensate can be estimated from the width of the long-wave emission spectrum [2]. Indeed, the width of the spectrum is determined by the sum of the Fermi energies of the degenerate electrons and holes

$$F_e + F_h = \frac{h^2}{2}\left(\frac{3}{8\pi}\right)^{2/3}\left(\frac{1}{m_e} + \frac{1}{m_h}\right)n_o^{2/3}$$

and amounts to approximately 25 meV (Fig. 3). The effective masses for the state densities in the silicon are $m_e = 0.86$ m and $m_h = 0.49$m [6], whence n_0 = 3×10^{18} cm^{-3}. This is larger by approximately one order of magnitude than the carrier density in the condensed phase of the germanium [2].

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