Cross section for binding of free carriers into excitons in germanium

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The kinetics of photoconductivity produced as a result of ionization of excitons in germanium by submillimeter radiation have been investigated. The cross section for binding σ_{bind} of free carriers into excitons in the 1.5 to 8-K temperature range has been determined. It was found that σ_{bind} is larger than the cross section for capture of carriers by an attracting shallow donor or acceptor, which was measured by the same method,[1] and that it has a different temperature dependence.

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Despite the large amount of effort that has been expended on studying free excitons in germanium and their condensation, the process of carrier binding in excitons has hardly been investigated experimentally. It has been impossible to measure the free-carrier densities and the binding cross section σ_{bind} over a broad range of temperatures because of the difficulties of separating the competing mechanisms of band-to-band recombination, the effect of exciton dissociation at high temperatures ($T > 4$ K), and their condensation at low temperatures. Although this can be accomplished more easily in silicon, only one paper, as far as we know, has been published on this subject.[2]

The theory of carrier binding into excitons, however, has recently been developed extensively. A calculation method, which had previously been used successfully for impurity centers,[4] was used in Ref. 3 for the binding process of free carriers in excitons. The cascade recombination of an electron-hole pair is regarded as a diffusion in total-energy space, and special attention is focused on the energy dissipation due to the motion of the center of mass of an electron-hole pair and the energy exchange between the internal and translational motion of the exciton. This additional channel of energy loss, as compared with the recombination at impurity centers, gives a larger value of σ_{bind} and a different temperature dependence. The results of

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theoretical calculations can be used for Ge with much greater accuracy than for Si, since most of these calculations were carried out by assuming that the electron mass is markedly different from the hole mass.

The measurements of submillimeter photoconductivity and absorption spectra, which have become possible because of the development of backward-wave-tube spectrometers,[5] would seem to open large possibilities for studying the binding process of free carriers into excitons. These instruments make it possible to measure the wave band corresponding to the exciton binding energy in germanium,[6] and therefore to separate the binding into excitons from other competing band-to-band recombination mechanisms, and also to measure the time of transient processes down to 10^{-9} sec. Measurements by both the steady-state and non-steady-state method are necessary in order to obtain reliable values of the binding cross section, since the first method generally does not give accurate absolute cross sections, while in the second method the re-emission of nonequilibrium carriers from the higher excited states of the cascade-recombination centers[1] has a strong influence on the results. In addition, we are able to compare the binding of carriers into excitons with the capture of carriers by shallow donors and acceptors investigated by the same method.

The experiment was performed in the wave band $\lambda = 0.5$-0.25 mm in the temperature interval $T = 1.5$–10 K on Ge samples with donor and acceptor densities of 10^{10}–10^{12} cm^{-3}. The principal measured quantities were the photocarrier density Δn excited by the submillimeter radiation and the relaxation time τ_r of the submillimeter photoconductivity. However, the $\tau_r(T)$ dependence even for a constant band-to-band excitation level is determined not only by the variation of the binding cross section with temperature, but also by the variation of the density of neutral exciton centers (N_{ex}), whose ionization leads to the submillimeter photoconductivity, and the density of trapping centers (N_t), whose role is played by carriers of the opposite sign. Therefore, we have measured Δn, n, N_{ex}, and τ_r as a function of temperature and of the level of band-to-band excitation. The Δn and n values were determined from the area of the cyclotron resonance line at a frequency of 36 GHz, N_{ex} was determined from the absorption coefficient of the submillimeter radiation in the photoionization of the excitons,[6] and τ_r was determined from the dependence of the photoconductivity on the modulation frequency of the submillimeter radiation.

The dependences of the steady-state lifetime τ, which is proportional to $\Delta n/N_{ex}$, and of the photoconductivity relaxation time τ_r on n and T were determined from these data. To determine the absolute value of τ, we must also measure the free-exciton lifetime τ_{ex}. In fact, as low temperatures when there is no thermal dissociation and the recombination of electrons and holes proceeds via the excitons, $n/\tau = N_{ex}/\tau_{ex}$. To determine τ_{ex}, we measured the dependence of the submillimeter-radiation absorption coefficient on the modulation frequency of the band-to-band light. The characteristic decay frequency of this dependence gave the value of τ_{ex}; samples with $\tau_{ex} = 4$–8 μsec were chosen for the measurements.

Figure 1 shows the dependence of τ and τ_r on n at $T = 4.2$ K. They are the same for all samples investigated. We can see that $\tau \sim n^{-1}$ (dashed line and that it is appreciably smaller than τ_r. We explain the difference between τ_r and τ by the re-emission of carriers from the high excited states of excitons, which appear as trapping levels.

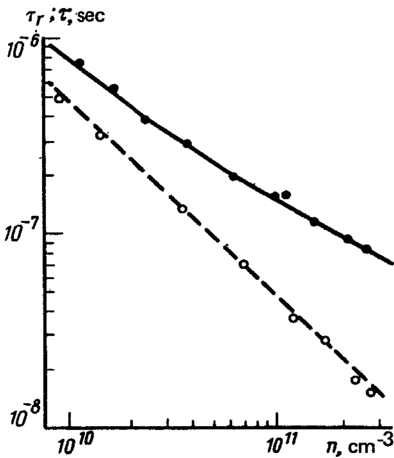

FIG. 1. Dependences of the lifetime (○) and of the relaxation time (●) of the submillimeter photoconductivity for the binding of carriers into excitons on the free-carrier density n (T = 4.2 K).

The solid line in this figure shows the $\tau_r(n_r)$ dependence obtained in accordance with Ref. 1 which was devoted to an analogous study of shallow inpurity centers. The agreement of the solid curve in Fig. 1 with the experimental data indicates that the trapping of carriers in the high excited states of shallow impurities and excitons has the same effect on the relaxation of excess-carrier density.

The measured temperature dependences of Δn, n, and N_{ex} make it possible to obtain the binding cross sections in the temperature range of 1.6 to 8 K. These results are shown in Fig. 2, together with the corresponding data for shallow donors and acceptors in Ge obtained by the same method—from the kinetics of submilli-

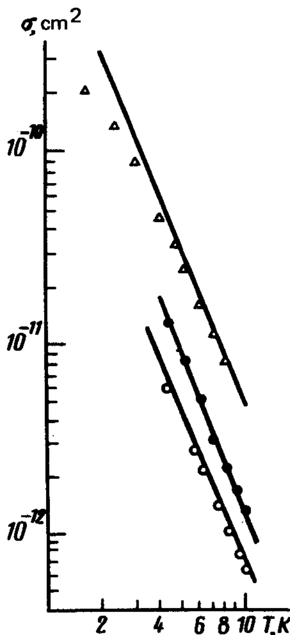

FIG. 2. Temperature dependences of the cross sections for capture of carriers by shallow donors (●) and by acceptors (○) and of the cross section for binding of free carriers into excitons (Δ).

meter photoconductivity.[1] Also shown here are the theoretical curves for excitons[3] and for impurities.[4] The cross section for binding into excitons is consistent with the theory[3] but is higher than the capture energy of carriers by donors and acceptors: for example, at $T=4.2$ K σ_{bind} is $\sigma_{\text{bind}}=3.2\times 10^{-11}$ cm^2, and the cross sections for capture by donors and acceptors are $\sigma_D=1.4\times 10^{-11}$ cm^2 and $\sigma_A=6\times 10^{-12}$ cm^2, respectively. We note that σ_{bind} has a weaker temperature dependence in the measurement range. The temperature interval used in the measurements is important in the comparison of the cross section for binding into excitons with that for the capture by an impurity. According to Ref. 3, at $T=1$–10 K the main role in the binding for Ge play those distances between the electron and the hole for which the total-energy relaxation rate is comparable with the energy exchange rate between the internal and translational motions of the exciton. The calculation is very complicated in this temperature interval. At lower T (for Ge at $T<1$ K) the binding process is the same as the capture at an impurity, and at $T>10$ K the energy relaxation is determined by the cooling of hot electrons to the ground state.

In conclusion, we should note that the free-carrier recombination mechanism does not change at $T=1.6$–2.2 K when the condensation of excitons reduces significantly their density.

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