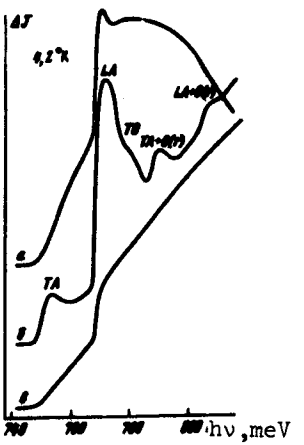
KINETIC PROPERTIES OF EXCITONS AND GERMANIUM PHOTOCONDUCTIVITY SPECTRA

E.F. Gross, A.V. Il'inskii, B.V. Novikov, and N.S. Sokolov
Institute of Semiconductors, USSR Academy of Sciences
Submitted 7 August 1970
ZhETF Pis. Red. 12, No. 5, 259 - 262 (5 September 1970)

The electron structure of the exciton has by now been sufficiently well studied. The kinetics of the excitons, however, have been much less investigated [1]. This is due to the considerable difficulties encountered usually both in the theoretical analysis and in the experiments aimed at the study of the kinetic properties of excitons. Since excitons are neutral formations, no direct transfer of charge accompanies their motion. As a result of various mechanisms of photoactive exciton decay [1], however, free carriers appear in the crystal and cause the photoconductivity of semiconductors; at the same time, these carriers bear information concerning the processes of exciton annihilation [2], including their interaction with impurity centers.

In order to obtain such information, we investigated the spectral distribution of the photoconductivity of pure and doped germanium at low temperatures (2 - 4°K). The investigations were carried out in the region of indirect exciton transitions, where the absorption coefficient is small (to 10 cm^{-1}) and the influence of the surface can be neglected.

Taking into account the possibility of impact ionization of the excitons [3] and of the impurity centers [4] even in electric fields of 3 - 6 V/cm, we paid particular attention to the electric field intensity at which the photoconductivity was investigated. The field intensity in the samples was determined with the aid of probes.



Spectral distribution of the photoconductivity of germanium at different electric-field intensities (the ordinate scales are different for curves a, b, and c; a - 0.05 V/cm, b - 1.5 V/cm, c - 4.0 V/cm).

At large electric field intensities, the form of the photoconductivity spectrum correlates with the absorption-coefficient spectrum [5 - 7]. The photoconductivity spectrum shows clearly two steps corresponding to production of excitons with excitation of TA and LA phonons (Fig. c). When the field is decreased, sharp maxima appear in the region where the exciton-absorption steps begin (Fig. b). In still weaker fields, these maxima practically disappear again (Fig. a).

Since no such dependence of the photoconductivity structure on the field intensity is observed in the purest crystals, we have assumed that its appearance is due to ionization of the impurity centers upon capture of excitons. This phenomenon was considered theoretically by Trlifaj [8], who has shown that the strongest interaction between the excitons and the impurity centers occurs at low exciton velocities. Therefore, when excitons with low kinetic energy are produced, and hence with low velocity (at the start of the steps), a large photocurrent arises. When the energy of the excitons produced by the light is decreased, the photocurrent changes little, since the excitons become thermalized if their lifetime is sufficiently large, and their velocities decrease to values that are effective, according to Trlifaj, for interaction with the

impurity centers. These arguments explain qualitatively the form of the photoconductivity spectrum in the case of weak fields (Fig. a).

In stronger fields, the probability of impact ionization of the excitons by free carriers becomes appreciable. The excitons do not have time to become thermalized during their lifetime, and when they interact with the impurity centers they still have the kinetic energy with which they have been produced. The photoconductivity spectrum reflects in this case the dependence of the cross section $\sigma(v)$ for the capture of the excitons by the impurity centers on the exciton velocity. At low kinetic energies the photocurrent is maximal and decreases rapidly with increasing kinetic energy, and hence with increasing exciton velocity. This leads to the appearance of the maxima at the starts of the exciton-absorption steps (Fig. b). An analysis of the shapes of these maxima makes it possible to determine the $\sigma(v)$ dependence.

With further increase of the electric field intensity, the lifetime of the excitons due to impact ionization by the free carriers is decreased to such an extent, that the exciton diffusion length becomes smaller than the average distance between the impurities. The photoconductivity mechanism considered above becomes insignificant, and we obtain the ordinary spectral distribution of the photosensitivity of the germanium, determined by the course of the absorption coefficient and by the photoactive decay of the excitons as a result of the impact ionization by the free carriers (Fig. c).

Besides the main maxima (TA and LA), there are observed on the short-wave part of Fig. b two weaker maxima, TA + $O(\Gamma)$ and LA + $O(\Gamma)$, which are shifted relative to the main maxima by an amount equal to the energy of the optical phonon at the center of the Brillouin zone [9]. The appearance of these maxima allows us to assume that at these points of the spectrum excitons with low velocities are produced. This is possible either as the result of two-phonon indirect absorption, or as a result of the rapid relaxation of the kinetic energy of the excitons with excitation of optical phonons [10, 11]. The latter assumption seems to us more probable, since no two-phonon transitions have been observed in the spectra of indirect exciton radiation in germanium [12]. The different ratio of the intensities of processes in which one and two photons participate for the TA and LA maxima can be explained by recognizing that the single-phonon process in germanium is forbidden if the TA phonon is to participate and allowed for the LA phonon.

In conclusion, the authors are sincerely grateful to S.A. Permogorov for a useful discussion of the results.

[1] R.S. Knox, Theory of Excitons, Academic Press, 1963.
[2] E.F. Gross and. B.V. Novikov, J. Phys. Chem. Sol., 22, 87 (1962).
[3] V.M. Asnin, A.A. Rogachev, and S.M. Ryvkin, Fiz. Tekh. Poluprov. 1, 1740 (1967) [Sov. Phys.-Semicond. 1, 1445 (1968)].
[4] E.I. Zavaritskaya, Trudy FIAN 37, 41 (1966).
[5] G.G. MacFarlane, T.P. McLean, J.E. Quarrington, and V. Roberts, J. Phys. Chem. Sol. 8, 388 (1959).
[6] B.V. Novikov, E.F. Gross, and M.A. Drygin, ZhETF Pis. Red. 8, 15 (1968) [JETP Lett. 8, 8 (1968)].
[7] E.F. Gross, A.V. Il'inskii, B.V. Novikov, and N.S. Sokolov, Fiz. Tverd. Tela 11, 3007 (1969) [Sov. Phys.-Solid State 11, 2437 (1970)].
[8] Trlifaj, M., Czech, J. Phys. 9, 446 (1959).
[9] B.N. Brockhouse, Phys. Rev. Lett. 2, 256 (1959).
[10] E.F. Gross, A.V. Ilynskii, K.F. Lieder, B.V. Novikov, and N.S. Sokolov, Phys. Stat. Sol. 34, K59 (1969).
[11] E.F. Gross, S.A. Permogorov, V.V. Travnikov, and A.V. Selkin, J. Phys. Chem. Sol. (to be published).

[12] Benoit a la Guillaume, O. Parodi. Proc. Int. Conf. on Semicond. Phys., p. 426, Prague, 1960.