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SIXTH ALL-UNION SEMINAR ON "EXCITONS IN CRYSTALS"

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THE Sixth All-union seminar on "Excitons in Crystals" took place from 25—29 May, 1970 at the Institute of Solid State Physics of the U.S.S.R. Academy of Sciences in Chernogolovka. The seminar was devoted to bound and dissociated exciton states and was conducted in the form of an extensive discussion of a number of invited review reports. About 150 people from the leading research institutes of the Soviet Union participated at the meetings of the seminar.

Bound exciton states in extrinsic semiconductor crystals were dealt with in two review reports.

In a paper presented by **I. B. Levinson** (the L. D. Landau Institute of Theoretical Physics, U.S.S.R. Academy of Sciences, Chernogolovka) the theoretical concepts about the interaction of an exciton with a localized center, based on the effective mass approximation, were considered. The main attention in the report was focused on the problem of stability of weakly bound exciton complexes of the quasimolecular type, using, as an example, excitons localized near neutral (ionized) acceptor and donor centers. He analyzes the essential peculiarity of the spectroscopy of weakly bound exciton complexes in semiconductors, a peculiarity which lies in the fact that the oscillator strengths of the optical transitions to such states are anomalously large in crystals in which the nearest extrema of the bands are located at the center of the Brillouin zone (the optical transitions are direct) and, inversely, anomalously small in crystals in which the optical transitions are not direct.

The spectroscopic and magnetospectroscopic properties of exciton complexes in elementary (Si, Ge) and binary (II-VI and III-V) semiconductors are considered in detail in a paper presented by V. B. Timofeev (Institute of Solid State Physics, U.S.S.R. Academy of Sciences, Chernogolovka). The processes of radiative recombination via bound exciton states are analyzed and the efficiencies (quantum yields) of the radiative recombination of the excitons localized near isoenergetic impurities, donor and acceptor (neutral and ionized) centers as well as the recombination radiation of electron-hole pairs, are contrasted. Problems connected with Auger recombination of localized excitons in semiconductors are considered.

A number of the participants of the seminar took part in the discussion of the contents of these reports. **V. I. Sugakov** (State University, Kiev) drew attention to the possibility of experimental observation of anomalously low values of oscillator strengths for optical transitions in exciton complexes for definite relations between the effective masses of the electron and hole which are constituent parts of the complex. **G. M. Bartenev** (the V. I. Lenin Moscow State Pedagogical Institute, Moscow) read a paper on the states of the positronium atom in ionic crystals. **I. S. Gorban'** (State University, Kiev) reported on the properties of exciton complexes, due to the bound states of an exciton with nitrogen centers, in silicon carbide crystals.

One of the extraordinary meetings of the seminar was devoted to a discussion of a paper presented by **S. A. Permogorov** (Institute of Semiconductors, U.S.S.R. Academy of Sciences, Leningrad) on the observation of polariton (exciton-photon) states in cadmium sulfide and an experimental method which makes it possible to investigate the dispersion of the polariton branches in the neighborhood of $k = 0$. The method is based on the study of the combination scattering of polaritons for which, as was shown by the speaker, the scattering cross-sections turn out to be extraordinarily large.

Bound and dissociated states of Frenkel excitons were dealt with in three review reports. In a paper presented by **É. I. Rashba** (L. D. Landau Institute of Theoretical Physics of the U.S.S.R. Academy of Sciences, Chernogolovka) entitled: "The Theory of Bound and Dissociated Exciton States in Molecular Crystals," two types of bound states were considered. The states of the first type pertain to electron excitations and arise when an exciton is captured by an unexcited impurity molecule. Bound states of the second type correspond to vibrational excitations of the crystal and arise as a result of the interaction of the exciton with phonons (one or several), corresponding to one of the intramolecular oscillations of the molecules of the crystal or the impurities in it. Bound states of both types are produced as a result of the separation of the corresponding energy spectrum from the continuous spectrum of the dissociated states. In the first case, such a dissociated state is an exciton band, in the second—two-particle vibrational states.

The conditions for the separation of the spectra of the bound states as a function of the binding energy of an exciton with an impurity molecule or phonon and of the parameters of the continuous spectra are considered.

A review of the experimental investigations of impure molecular crystals was made in a paper read by **V. L. Broude** (Institute of Solid State Physics, U.S.S.R. Academy of Sciences, Chernogolovka). Using as an example the analysis of the absorption and luminescence spectra of isotope-admixed crystals, he showed that such fundamental characteristics of impurity spectra as: 1) positions, 2) integrated intensities, 3) polarization relations and 4) shapes of impurity absorption bands—extraordinarily sharply depend on the binding energy of an exciton in an impurity molecule and on the parameters of the exciton bands of the crystal-solvents. A complete quantitative agreement between the experimental and the theoretically computed relationships is shown.

A paper presented by **E. F. Sheka** (Institute of Solid State Physics, U.S.S.R. Academy of Sciences, Chernogolovka) was devoted to a review of experimental inves-

tigations of vibrational states in molecular crystals. The manifestation of bound and dissociated vibrational excitations in absorption spectra is illustrated with the analysis of the vibrational absorption spectra of a number of pure and isotope-admixed crystals, and a quantitative analysis of the fundamental characteristics of the bound and dissociated absorption bands is made. It is shown on the basis of an independent calculation in accord with the theory developed by Rashba, that the existing theory of vibrational states describes the experimental data well and points to the possibility of an independent determination of the density of states in the exciton bands.

Many participants of the seminar took part in the discussion of these reports. **V. I. Sugakov** (State University, Kiev), **N. I. Ostapenko** and **M. T. Shpak** (Institute of Physics, Academy of Sciences of the Ukrainian SSR, Kiev) talked about localized exciton states, due to the presence of defective molecules of the solvent in impure crystals, and their connection with the structure of the exciton bands in naphthalene crystals.

Three lectures were given on the vibrational spectra of the aromatic crystals. **V. M. Agranovich, Yu. E. Lozovik,** and **M. A. Mekhtiev** (Institute of Spectroscopy, U.S.S.R. Academy of Sciences, Krasnaya Pakhra, Moscow Region) drew attention to the effect of anharmonicity on the spectrum of localized and surface vibrations in molecular crystals. **I. A. Korotkov** (State University, Kiev) dwelt on the problems of the experimental investigation of exciton states in the spectra of combination scattering. **G. N. Zhizhin** and **M. A. Moskaleva** (Institute of Spectroscopy, U.S.S.R. Academy of Sciences, Krasnaya Pakhra, Moscow Region) reported on measurements of the concentration dependence of the magnitude of the Davydov splitting in the vibrational spectrum of the crystal solution thiophene-thiophene-d_2.

A paper read by **V. V. Eremenko** (Physico-technical Institute of Low Temperatures, Academy of Sciences, Ukrainian SSR, Khar'kov) aroused great interest in the audience. This paper was devoted to a review of the experimental and theoretical investigation of exciton-magnon states in antiferromagnetic crystals. In the overwhelming majority of crystals, which have been investigated to date, the exciton-magnon companions are complex two-particle states. Bound exciton-magnon states together with the two-particle states have as yet been observed in only MnF_2 crystals. The main attention in the review was given to the connection of the shape of the bands, which are due to the excitation of exciton-magnon states, with the structure of the exciton and magnon bands, and to the dependence of this structure on the magnetic characteristics of the crystal.

A specific type of dissociated state, namely, of the cooperative exciton and localized states, was considered in papers "The Cooperative States of an Oxygen Crystal" by **A. F. Prikhot'ko** (Institute of Physics, Academy of Sciences of the Ukrainian SSR, Kiev) "The Cooperative States and Cooperative Luminescence of Nonmetallic Crystals" and by **E. D. Trifonov** (A. A. Zhdanov University, Leningrad). During the discussion on these reports, **V. A. Benderskiĭ** (Associated Institute of Chemical Physics, U.S.S.R. Academy of Sciences, Chernogolovka) read a paper on the kinetic properties of annihilative singlet excitons in an anthracene crystal.

A separate session of the seminar was devoted to a discussion of the collective effects in a system of excitons. This session was opened with a review report by **S. V. Moskalenko** (Institute of Applied Physics, Academy of Sciences of the Moldavian SSR): "Experimental and Theoretical Investigations of Biexcitons." First put forward by the author, the idea of the possibility of formation of exciton molecules under conditions of sufficiently large exciton concentrations has been developed in papers by many authors. The new structure in exciton absorption and luminescence spectra, predicted by them, stimulated the search for it and its subsequent discovery in the spectra of a number of crystals under conditions of strong optical pumping.

The lecturer also remarked that in a system of dense electron-hole gas, there can be other formations, e.g. drops. The possibility of a Bose-Einstein condensation is not to be ruled out. In his lecture **L. V. Keldysh** (P. N. Lebedev Institute of Physics, U.S.S.R. Academy of Sciences, Moscow) paid much attention to the possibility of formation of different bound states in a system of excitons. L. V. Keldysh noted that since liquid drops and biexcitons can appear in a number of phenomena to the same extent, additional special experiments are needed for a convincing interpretation of the observed effects.

Many participants of the seminar took part in the discussion of the questions touched upon. **E. F. Gross** (A. F. Ioffe Physico-technical Institute, Leningrad) jointly with **F. I. Kreĭngol'd** reported a new experimental observation of biexciton luminescence in a Cu_2O crystal. The spectrum of this radiation is a series of bands obeying the same serial laws as the "green" exciton series in Cu_2O absorption.

Ya. E. Pokrovskiĭ and his co-workers (Institute of Radio Engineering and Electronics, U.S.S.R. Academy of Sciences, Moscow) communicated a series of data confirming the production of a liquid from excitons in silicon and germanium crystals and indicating the very important role of impurities (in particular, boron impurities) as centers of condensation of the drops. **O. V. Gogolin, V. S. Bagaev,** and **T. I. Galkina** (P. N. Lebedev Institute of Physics, U.S.S.R. Academy of Sciences, Moscow) talked about the radiation of a system of excitons in a germanium crystal during a uniaxial compression. As shown by the authors, the selective sensitivity of the locations of the luminescence lines of the bound states of this system to the magnitude and direction of the applied stress attests to the production and motion of electron-hole drops in this crystal. A lecture by **É. L. Nolle** (P. N. Lebedev Institute of Physics, U.S.S.R. Academy of Sciences, Moscow) dealt with the problems of the interaction between excitons and of the stimulated radiation of cadmium telluride caused by the excitons. To close the discussion, L. V. Keldysh remarked that existing experiments do not at present give a definite answer to the question of the fate of a system with a high exciton density. One of the principal arguments in favor of biexcitons is the square-law

variation in optical spectra. At the same time, experiments on pressure undoubtedly attest to the existence of drops.

In conclusion of the seminar, a resolution was adopted at a meeting of the Permanent Organizing Committee to hold the next session of the seminar in Tartu in the Estonian SSR in June 1971.

Translated by A. K. Agyei