

THIRD CONFERENCE ON THE THEORY OF SEMICONDUCTORS

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THE Third Conference on the Theory of Semiconductors took place in L'vov from the 2nd to the 9th of April 1959; it was convened by the Commission on Semiconductors of the U.S.S.R. Academy of Sciences and the Commission on Semiconductors of the Ukrainian S.S.R. Academy of Sciences, together with the I. Franko L'vov State University.

More than 200 representatives from numerous scientific institutions in Moscow, Leningrad, Kiev, Sverdlovsk, Khar'kov, L'vov, Minsk, Tbilisi, Tartu, et al., took part in the Conference. In all, 86 papers were presented, of which 37 were given in 7 plenary sessions.

The Secretary of the L'vov Regional Committee of the Ukrainian Communist Party — Comrade **F. T. Koval'** — first addressed the Conference participants. F. T. Koval' dwelt on the tasks set before the Soviet people by the Twenty First Congress of the Communist Party of the Soviet Union, in particular those set to the men of science and culture, reviewed the economic and cultural achievements in the western regions of the Ukraine, and described to the Conference participants the tasks before the workers of L'vov in connection with the Seven Year Plan.

On behalf of the Council of the L'vov State University, the Pro-rector, Prof. **A. I. Yurzhenko**, welcomed the gathering. Prof. **S. I. Pekar**, opening the Conference, briefly outlined the development of semiconductor physics in the Soviet Union in the two and a half years which had elapsed since the Second Conference on the Theory of Semiconductors; he remarked on the great increase both in the amount of work on the theory of semiconductors, and in the number of physicists working in this field, due especially to the influx of young scientists.

The many-electron theory of the solid state was the subject of a large group of papers. The paper by **S. V. Vonsovskii**, **M. Sh. Giterman**, **G. I. Gusev**, **G. G. Taluts**, "On the Many-Electron Interpretation of Excitons," dealt with the separation, from the general Hamiltonian of a system of interacting electrons in a crystal, of the various types of elementary excitation, and discussed their relation to types of excitation previously obtained. The treatment was carried out using the method of collective coordinates and momenta. As collective coordinates $\rho_{\mathbf{k}}$, the Fourier components of the electron density are chosen; in terms of the second quantization

$$\rho_{\mathbf{k}} = \sum_{\alpha\alpha'} q_{\mathbf{k}}(\alpha, \alpha') a_{\alpha}^{\dagger} a_{\alpha'}$$

The collective momentum

$$\pi_{\mathbf{k}} = -i\hbar \sum_{\alpha\alpha'} q_{\mathbf{k}}'(\alpha, \alpha') a_{\alpha}^{\dagger} a_{\alpha'}$$

From $\rho_{\mathbf{k}}$ and $\pi_{\mathbf{k}}$ the Bose operators $b_{\mathbf{k}}^{\dagger}$ and $b_{\mathbf{k}}$ are constructed. The Hamiltonian is expanded in power series of $b_{\mathbf{k}}^{\dagger}$ and $b_{\mathbf{k}}$. The Hamiltonian is diagonalized in the effective mass approximation. The energy spectrum of the plasma and exciton oscillations is determined. Also studied were the oscillation spectra in external fields. Account of the electron-phonon interaction leads, in the case of an ionic crystal, to a reduction of the activation energy of exciton states and an increase of their effective mass. In an external uniform electric field a decrease in the order of the Stark effect occurs for excitons, as compared with the usual effect of level displacement in isolated atoms.

In the paper by **V. I. Cherapanov** and **V. S. Galishev** were presented the results of work aimed at obtaining the selection rules for optical exciton transitions in the dipole and quadrupole approximations. The optical selection rules had been obtained earlier,¹ but only for the exciton orbital quantum number in the dipole approximation. In the case of excitons it is necessary to bear in mind spatial dispersion; in so far as the dipole approximation neglects this dependence, the quadrupole approximation takes it into account. It was shown that the potential energy of interaction of an electron and a hole takes the form

$$V(\beta) = -\frac{e^2}{\beta} \Phi(\kappa\beta),$$

where $\Phi(x)$ is the probability integral. For large β it goes over to the Coulomb form. For small β it does not correspond to a Coulomb law; this removes the energy degeneracy with respect to the orbital quantum number. The selection rules in the dipole approximation can be obtained in the usual way; they have the following form:

$$k=0; \quad l=1; \quad m=0, \pm 1$$

(l is the orbital and m the magnetic quantum number).

The selection rule for optical exciton transitions in the quadrupole approximation is:

$$k=0; \quad l=0,2; \quad m=0, \pm 1, \pm 2.$$

Taking into account quadrupole transitions provides the possibility of explaining the fine structure of the exciton spectrum in cuprous oxide, as observed by Gross and co-workers.² As **Yu. A. Firsov** pointed out

in the discussion, a much greater energy splitting with respect to the orbital quantum number l is obtained on taking into account the type of symmetry of the problem.

A calculation of the thermal conductivity due to excitons was given in the paper by **E. N. Agafonova** and **I. A. Korunova**, "A Calculation of the Effect of Bose Excitations on the Thermal Conductivity of Atomic Semiconductors." Agreement of the experimental data with the Wiedemann-Franz law is observed for the electronic contribution to the thermal conductivity. However, at some temperatures an additional thermal conductivity κ' is observed, which is independent of the concentration of current carriers and changes with temperature according to the law $\kappa' \sim \exp(-B/kT)$ ($B \ll$ the width of the forbidden gap). A qualitative explanation of the thermal conductivity of atomic semiconductors (in particular, of the term κ'), is given from a single viewpoint in terms of the many-electron model. In the method,³ the Bose and Fermi electronic excitations are separated. The energy transferred by quasi-particles of all types is calculated using the kinetic equations. The part of the thermal conductivity which follows the Wiedemann-Franz law is explained by the Fermi quasi-particles. The participation of the Bose quasi-particles in the transfer of energy just gives the additional thermal conductivity κ' .

A new form of the polar model of a crystal was given in the paper by **A. E. Glauberman**, "Theory of Elementary Excitations in Semiconductors." The new method of "re-labelling" enables a simple Hamiltonian of the elementary excitations to be constructed, and, after subsequent separation of the ground state, it leads to the correct statistics for the excitations and possesses generality and simplicity.

For an atomic crystal with a single s-valence electron on each atom in the ground state, if one is restricted only to s states of the electrons, the excitations will be doublets and holes. If the Hamiltonian of the crystal in the second quantization representation is written in the form

$$H = u_0 + \sum_{\alpha\alpha'} L(\alpha, \alpha') a_{\alpha}^+ a_{\alpha'} + \frac{1}{2} \sum_{\alpha_1\alpha_2\alpha'_1\alpha'_2} F(\alpha_1, \alpha_2, \alpha'_1, \alpha'_2) a_{\alpha_1}^+ a_{\alpha_2}^+ a_{\alpha'_2} a_{\alpha'_1},$$

(where the index α labels the number of the lattice cell, the state of the valence electron, and its spin) then the transition to the Hamiltonian of the excitations is accomplished using the canonical transformation

$$a_{q1/2}^+ = A\alpha_q^+ + B\beta_q; \quad a_{q-1/2}^+ = B\alpha_q^+ - A\beta_q;$$

$$A = \sqrt{\frac{n}{m+n}}; \quad B = \sqrt{\frac{m}{m+n}},$$

where m and n are the concentration of ground states of the cells, and α and β are the operators for doublets and holes, respectively. Thus, the operators of polar excitation (doublets and holes) are operators of the Fermi type.

To discuss Frenkel excitons it is necessary to take account in the Hamiltonian of the creation and annihilation

operators of p states, for which "re-labelling" in operators of the lattice sites is carried out

$$a_{qp1/2}^+ = \eta_q^+, \quad a_{qp-1/2}^+ = \xi_q^+,$$

and the operators of excitons are introduced using the following relations:

$$T_q^+ = \eta_q^+ \beta_q^+, \quad S_q^+ = \xi_q^+ \beta_q^+.$$

Here the operators β no longer correspond to the operators for true holes. It is easy to obtain expressions for the operators α , β , η , ξ in terms of the operators for the actual quasi-particles, doublets, holes and excitons. The hole operators are of a quasi-Fermi, the exciton operators of a quasi-Bose and the doublet operators of a Fermi type.

The case of a crystal with saturated-spin ground state (two s electrons on each atom) is also considered. The elementary excitations are discussed: singlets, triplets and excitons. The operators are re-labeled

$$a_{qp1/2}^+ = \alpha_{q1}^+, \quad a_{qs1/2}^+ = \beta_{q1},$$

$$a_{qp-1/2}^+ = \alpha_{q2}^+, \quad a_{qs-1/2}^+ = \beta_{q2}.$$

The exciton operators occur here, as products of the type $\alpha^+ \beta^+$. It is easy to obtain formulae expressing the operators α and β in terms of the operators of the actual quasi-particles. Triplets and singlets are quasi-Fermi, but excitons are quasi-Bose.

In a similar way, it is easy to discuss a displaced ground state, which is important in practice for the problem of semiconductors containing impurities. From the scheme developed a number of new results follow, which are of especial interest in the presence of an external magnetic field.

In the discussion **S. I. Pekar** pointed out that the theory described, as well as earlier variants of the polar model, does not take into account the dependence of the p state and its energy on the vacant or filled s state in the cell (and, on the other hand, the dependence of the s state on the filling of the p state). **A. E. Glauberman** replied that the neglect of this type of correlation does not affect the qualitative results of the theory, and that when it is necessary it can be taken into account by a corresponding choice of the system of basis functions.

The contribution by **V. L. Bonch-Bruевич**, "Some Problems in the Theory of Electron-Hole Plasmas in Semiconductors," was devoted to the occurrence in semiconductors of collective ("plasma") effects of the type observed in gaseous discharges. The distinction from gaseous discharges is that in semiconductors the concentration of free charges can be much greater ($10^{17} - 10^{18} \text{ cm}^{-3}$); it can be comparatively easily varied within quite wide limits; the heavy particles can always be considered immobile; there is always damping due to collisions with phonons. These main types of "collective" effects take place: a) the appearance

of a new branch of the energy spectrum of plasma oscillations (compared with the ideal electron gas); b) the modification of the fermion spectrum — both parameters of the effective mass type and the form of the dispersion law itself change, due to the inter-electron interactions; c) the existence of damping due to the inter-electron interaction; d) the change of the form of the distribution function, due to interaction (in the quantum region); e) the screening of an external field by the free charges. The formalism of Green's temperature functions allows the study of the fermion spectrum to proceed to a solution of the "effective Schrödinger equation," having a formally "single-particle form," i.e., the usual ideas on local states associated with defects in the structure are preserved in the theory. By virtue of the screened interaction potential of an electron with an impurity center, the number of local states is finite, and can disappear for sufficiently small screening radius. This opens up the possibility of controlling in a known way the energy spectrum of the system by changing the concentration of free charge carriers and the temperature. Parameters such as the effective mass, impurity ionization energies, etc, depend on the concentration of charge carriers and temperature, i.e., they are characteristics, not of the substance, but of a specimen, and are thermodynamic quantities (able to experience fluctuations). **M. Ya. Azbel'** doubted whether there existed a region in which what had been said by the contributor applied, because the mean free path must be sufficiently small in order to speak of interactions. This corresponds to a very low temperature ($\sim 0.1^\circ \text{K}$).

A number of papers dealt specifically with the theory of excitons in crystals. In **S. I. Pekar's** paper,* "The Theory of Electromagnetic Fields in a Crystal in the Exciton Absorption Region," the results of previous work by the author⁴ were generalized, in the case of finite lifetime of the excited state of the crystal and for some of the optical absorption bands. Taking into account the finite lifetime of the exciton makes it possible to obtain general formulae for absorption and to correct previously derived dispersion formulae. For small and imaginary refractive index, the Schrödinger equation for the exciton is inapplicable. The calculation is therefore made by an electrodynamic method. The crystal is considered as an assembly of electrons and nuclei interacting with the electromagnetic field in vacuum. The electromagnetic wave exciting the crystal is introduced as a classical exciting field. The energy operator is written in the form $\hat{H} + \hat{W}$ (\hat{W} is the interaction operator with the external magnetic field). The state of the crystal excited by light is described by the wave function

$$\psi = \psi^0 + \sum_m C_m \psi_m; \quad |C_m| \ll 1.$$

*In distinction from other papers on excitons, **S. I. Pekar** considers the "generalized" exciton, a neutral excitation possessing a single quasi-momentum.

The correct initial conditions for C_m should take into account the fact that the absorption of light in the crystal is accompanied by the crystal being warmed up by the light absorbed. Polarization waves of thermal origin therefore appear in the crystal, the amplitude of which is not proportional to the field of the optical excitation, but depends on the duration of previous illumination, i.e., the polarization has two parts: "thermal" and "synchronized." Only the synchronized part of the polarization can be described by a complex dielectric constant. It is impossible to consider excitons as quasi-particles in the old sense of the word. When light is absorbed, a so-called "optical exciton" arises (a combination of optical and phonon waves).

The new form of the polarization vector leads to new phenomena in the dispersion curve (which vanish if the mass of the exciton $\rightarrow \infty$).

For the limiting exciton wavelength a dependence of energy on spatial direction is found. The region of optical absorption is determined by the relation $\hbar\omega \approx \epsilon_0$ (the energy of the ground state of the crystal) and not by the usual Bohr frequency rule $\hbar\omega = \epsilon$ (energy of the excited state). Whence it follows that experimental study of the frequency ω , for which the absorption is a maximum, allows the determination, using the relationship $\hbar\omega = \epsilon_0$, of the quantity ϵ_0 , which, in general, is smaller than the exciton energy ϵ . The result of taking into account the finite lifetime of the exciton is that the refractive index acquires a complex term, which determines the attenuation of a monochromatic wave in space. But, as was shown in reference 4, several plane waves arise in the crystal, each of which has its own refractive index and attenuation coefficient. The attenuation of the total intensity is not exponential. The phenomenological idea of an optical absorption coefficient loses its validity.

The new theory of electromagnetic waves in crystals in the region of exciton absorption, developed by **S. I. Pekar**, was applied to cubic crystals with isotropic effective exciton mass in the paper by **I. M. Dykman** and **S. I. Pekar**, "Light Waves in Crystals in the Exciton Absorption Region and the Impurity Photoeffect." It was shown that when the frequency of light is close to ω_0 , where $\hbar\omega_0$ is the smallest energy of the exciton state, the amplitudes of the transverse waves arising in the crystal are small. The longitudinal wave is dominant and its amplitude is of the same order of size as the incident amplitude. In the frequency interval for which the refractive index of the normal wave is significantly smaller than unity, the amplitudes of the normal transverse and the longitudinal waves can greatly exceed the amplitude of the incident wave. In the region under consideration a sharp increase in the number of photo-ionizations, and consequently in the value of the photo-current, should take place. Besides this, the photo-current should have in this frequency region a strong dependence on the angle of incidence and the polarization. This phenomenon can be one of

the mechanisms of the exciton impurity photo-effect observed by Zhuze and Ryvkin, Apker, Taft et al.

In the course of the discussion, **V. M. Agranovich** remarked that the results may be somewhat altered if the absorption of light is taken into account. **Yu. M. Popov** pointed out the necessity of comparing the authors' results with experimental data.

In the communication, "The Energy of the Exciton in Ionic Crystals," by **V. A. Moshalenko**, the calculation of the partition function of the exciton in ionic crystals was considered. After performing the summation over the Bose amplitudes of the phonon field, the partition function of the system under consideration appears in the form of a contour integral

$$Z = \chi \int \int \alpha R_0 dR_\beta d\tau_0 d\tau_\beta \delta(R_0 - R_\beta) \delta(\tau_0 - \tau_\beta) \int e^S D\mathbf{r} D\mathbf{R},$$

where S is the sum of the kinetic energies of the electron and hole, the energies of their self-interactions by means of the phonon field, and the energy of electrical and indirect interactions of the electron and hole. Using the variational theorem, Z is replaced by a simpler expression which permits exact functional integration. As a result of the calculations an expression is obtained for the partition function of the system for arbitrary values of the exciton-phonon interaction and for arbitrary temperatures. The expressions obtained give, in various limiting cases, the results of previous works on the theory of the exciton.

The theory of the exciton of large radius, taking into account both Coulomb and resonance interactions, was developed in the paper by **É. M. Rashba**, "The Effect of Resonance Excitation Transfer in the Theory of the Exciton of Large Radius." Two mechanisms exist for the motion of excitons: resonance (Frenkel excitons) and exchange (Mott excitons). In fact, the motion is more complicated; it is necessary to take into account both mechanisms. In the Wannier-Mott theory the possibility of electron-hole pairs being annihilated and created is not taken into account. Annihilation terms are introduced. The transition to the continuum, which is carried out under definite assumptions, leads to an integro-differential equation, containing a non-relativistic contact term.

In the paper of **A. G. Samoïlovich** and **A. A. Lipnik**, "The Formation and Disintegration of the Mott Exciton," results were reported of calculations of the probabilities of formation p_c and disintegration p_p of the exciton into acoustic phonons over a wide temperature range (starting at the limit of low temperatures). The calculation is carried through using the usual perturbation theory in the effective mass approximation. For the parameters approximately corresponding to Ge, p_c increases in the range from zero to hundreds of degrees Kelvin; this is explained by the increase in the number of phonons which are required for formation. This factor prevails in the range mentioned over the effect of the increase of electron and hole kinetic

energies. The probability of disintegration can be related to the probability of formation, and the lifetime of the exciton with respect to disintegration can be evaluated. For Ge, $\tau_p \sim 10^{-3}$ sec, at 4°K, and $\tau_p \sim 3 \times 10^{-12}$ sec at 100°.

S. I. Pekar drew attention to the fact that the idea of quantum capture may be inapplicable when capture occurs at large distances (then classical diffusion takes place). As **M. I. Kaganov** pointed out, to evaluate the quantum and classical behavior, it is necessary to compare the radius of the exciton with its free path.

The problem of calculating the free path length of a large radius exciton in polar crystals with cubic symmetry was analysed in a paper by **A. V. Tulub**, "The Free Path Length of the Exciton in Polar Crystals." The usual apparatus of perturbation theory in polar crystals can lead to important errors, since the interaction of an electron with the optical phonons is not weak. It is essential to take into account the interaction of the exciton with the phonons in the wave functions of the exciton referring to the initial and final states. The calculation of the scattering amplitude was performed by the Low method.

If the effective masses of the electron and hole coincide (as, for example, takes place in the case of cuprous oxide), the scattering cross section does not tend to zero. This is connected with the fact that, although the exciton as a whole will be an electrically neutral system, it does cause deformation of the lattice due both to the interaction of the electron and the hole with the medium. As a result, phonons experience scattering at the deformed lattice, and the scattering cross section will be finite. The usual perturbation theory does not take this fact into account.

The theory of F centers of large radius was also compared with the theory of excitons. It was shown that to take into account the static polarization around the vacancy, it is insufficient to introduce a dielectric constant ϵ into the Coulomb energy operator. It is essential to take into account the static polarization for the excited states of the F centers.

A series of papers dealt with the optical properties of semiconductors.

The theory of the absorption of long wave-length radiation in crystals was treated in the paper by **L. É. Gurevich** and **Z. I. Uritskiĭ**, "On the Theory of Infrared Absorption by Crystals." For frequencies $\omega < \omega_0$ (photo-effect threshold) absorption is possible: a) directly by lattice vibrations; b) by the formation of virtual excitations which disappear with the formation of phonons; c) by free carriers; d) by excitons. The absorption associated with the excitation by a light quantum of a virtual electron-hole pair, which then annihilates itself with the formation of one or several phonons, was studied. For this the authors worked out a perturbation theory method in the interaction representation for nonrelativistic interactions of electrons and holes with photons and phonons, based on analogy

with quantum electrodynamics. Phonons and electrons of large energies are important in the absorption, so that it is only possible to evaluate the order of the absorption coefficient, which is done in the approximation of linear dispersion for acoustic phonons and isotropic quadratic dispersion for optical phonons and electrons. The absorption is a maximum for the two-phonon process, as a consequence of which detail can appear on the absorption curve for frequencies equal to the sum of the maximum frequencies of any two such branches. The absorption is little affected by magnetic field. The absorption by free carriers was considered in the presence of a magnetic field for isotropic quadratic dispersion of the carriers. Absorption by an electron of a photon with the emission or absorption of one phonon is the most important process. Oscillations of the absorption coefficient in the region of the internal photoeffect were also discovered, which can be explained by the quantization of the electron and hole states in the magnetic field (they have been studied experimentally by Zwerdling and Lax, and by Gross, Zakharchenya, and Pavinskiĭ⁵).

In the paper by A. V. Sokolov and V. P. Shirokovskii, "On the Theory of the Optical Properties of Semiconductors," two basic quantities were determined which characterize the optical properties of the solid state: "the optical conductivity" $\sigma(\omega)$ and polarizability $\alpha(\omega)$. The first quantity is directly related to the absorption power of the substance; whilst for the determination of the optical constants n and k and the reflecting power R , it is necessary to know the polarizability of the substance as well as $\sigma(\omega)$. The absorption by free carriers depends on the destruction of the periodic structure of the crystal. Since the same factors are responsible for the electrical resistance of the substance, there should exist a correlation between the electrical properties and the absorption by free carriers. The usual kinetic equation is used for the calculation. In some crystals the conduction band or valence band consists of several overlapping bands. In such cases infrared absorption, caused by "interzone" transitions of free carriers is observed. The transition probability can be calculated in the framework of the kinetic equation. If the energy bands close up, maxima of the resonance type should appear on the absorption curve. Also discussed were the optical properties of uniaxial semiconducting crystals which depend only on transitions of electrons from the valence band to the conduction band. The expressions obtained for $\sigma(\omega)$ and $\alpha(\omega)$ show that a uniaxial semiconducting crystal is birefringent. This is due to the fact that the selection rules for transitions between valence band and conduction band are different for different directions of polarization. Also a new effect is predicted which relates the transparency of the crystal to radiation polarized along the hexagonal axis with the ideal reflection of radiation polarized perpendicular to this axis.

O. V. Konstantinov and V. I. Perel' in their paper, "The Effect of Spatial Dispersion on the Transmission of Electromagnetic Waves through Semimetals in a Strong Magnetic Field," obtained a general expression for the electrical and magnetic susceptibilities taking into account spatial dispersion. By introducing the density matrix, the mean quantum mechanical current is found, which consists of two components. The first includes the effect of fields lagging in time. The second (the magnetization current) does not contain a lag. The electrical conductivity and the magnetic susceptibility are related. A general expression for the current density in the case of homogeneous medium was obtained by Nakajima, using Kubo's method.⁶ However, Nakajima did not obtain an expression for the magnetic susceptibility and its relation to the electrical conductivity.

In the discussion, M. Ya. Azbel' pointed out the necessity of taking into account the boundary conditions; because of the anomalous skin-effect, it is also necessary that the thickness of the skin layer should be much greater than the thickness of the specimen. M. I. Kaganov remarked that the idea of relating kinetic and thermodynamic coefficients was very progressive.

Problems in the kinetics of charge carriers, the theory of transport processes, and breakdown in semiconductors, were dealt with in a large group of papers.

In the paper by A. G. Samoilovich, M. I. Klinger and L. L. Kornblit, "On the Statistical Theory of Linear Irreversible Processes," a new result of the general expressions for the non-equilibrium density matrix of a system, and the mean currents when small "mechanical" forces act on the system, were described; they were directly generalized for generalized statistical forces of the temperature gradient type (see reference 6). The equation of motion obtained for the density matrix is solved and with the usual determination of the mean currents general expressions are obtained for the kinetic coefficients $L_{\mu\nu}^j$. The important particular cases of transport in an electron-phonon system and in viscous liquid were considered. In the range of weak electron-phonon scattering, a way of using perturbation theory was described, which gives the possibility of calculating the contribution of any approximation to the small electron-phonon coupling constant α in the determined kinetic coefficient. The role of virtual transitions, and the criterion for their contribution to the kinetic coefficients to be small, were determined in the α^2 approximation. The formulae obtained were applied to cases of electron scattering by phonons when the electron gas is non-degenerate; thus were obtained single expressions for all regions of temperature (with weak coupling) for the electrical and thermal conductivities and the thermal emf of an ionic crystal. Using the non-equilibrium density matrix determined, the non-equilibrium distribution function $f(\mathbf{k})$ of charge carriers in an electrical field different from zero was accurately determined. In the

range of weak electron-phonon coupling, when the energy spectra for electrons and phonons are isotropic, and when the electrons are non-degenerate

$$f'(\mathbf{k}) = -\frac{\partial f_0}{\partial \epsilon_{\mathbf{k}}} \tau(\mathbf{k}) v_{\mu}(\mathbf{k}) E_{\mu}(\mathbf{k})$$

E and v are the constant electric field and the mean velocity of carriers in the state \mathbf{k} ; f_0 is the equilibrium distribution function of electrons; $\tau(\mathbf{k})$ is the relaxation time of electrons in the state \mathbf{k} . For $\tau(\mathbf{k})$ a single expression was obtained for the entire energy and temperature ranges; it is also true for inelastic collisions.

In the contribution by **Yu. P. Irkhin** and **E. A. Turov**, "On the Phenomenological Theory of the Electrical Conductivity of Ferrimagnetic Semiconductors," the energy spectrum and electrical conductivity of ferrimagnetic semiconductors, consisting of two sublattices with noncompensating magnetic moments M_1 and M_2 , were considered on the basis of the phenomenological theory of ferrimagnetic materials.⁷ Putting $M_1 = M_2$ or $M_1 = -M_2$, the particular cases of ferromagnetic or antiferromagnetic semiconductors, respectively, could be obtained.

The following types of magnetic anomalies in the electrical conductivity were obtained: a) anomalies close to the Curie point: at the transition into the ferromagnetic state, a decrease in the activation energy of carriers takes place; b) anomalies at the compensation point of ferrimagnetics: a minimum of the activation energy occurs; c) when there is strong interaction of the charge carriers with magnetic moments, a change of sign in the temperature coefficient of the electrical conductivity can occur, i.e., a metallic type of conductivity appears at the transition into the ferrimagnetic state and close to the compensation point; d) in the case of impurity conduction, as distinct from intrinsic conduction, an increase in the activation energy can also occur at the transition into the ferromagnetic state.

Problems in the scattering of conduction electrons were dealt with in the paper by **A. I. Ansel'm** and **I. G. Lang**, "The Theory of Two-phonon Scattering of Conduction Electrons in Atomic Crystals." The interaction potential of conduction electrons with thermal oscillations of the atomic lattice, in the deformed ion approximation, up to terms quadratic in the displacements $\mathbf{u}(\mathbf{r})$, was taken in the form

$$U(\mathbf{r}) = U_1 + U_2; \quad U_1 = -(\text{grad } V_1 \mathbf{u}) = -\sum_i \frac{\partial V}{\partial x_i} u_i,$$

$$U_2 = \frac{1}{2} (\text{grad grad } V) \quad \text{and} \quad u = \frac{1}{2} \sum_{ij} \frac{\partial^2 V}{\partial x_i \partial x_j} u_i u_j,$$

where u_i and x_i are the orthogonal components of the vectors \mathbf{u} and \mathbf{r} , V is the periodic potential which acts on the electron in the ideal crystal. Two-phonon interactions of conduction electrons with lattice vibrations come in in two ways: a) in the second approxi-

mation of perturbation theory in a linear form; b) in the first approximation of perturbation theory in a bilinear form.

In order to obtain the final result for a) processes, it is necessary to take into account damping. Many-phonon processes do not change the relaxation time τ_1 of single-phonon scattering. Processes b) above the Debye temperature also lead to a finite relaxation time τ_2 without taking damping into account. For two-phonon scattering, as opposed to single-phonon scattering, longitudinal and transverse acoustical vibrations play an equal part. Also, on increasing the temperature, the role of two-phonon compared with one-phonon processes becomes greater. The temperature for which one- and two-phonon processes become of equal effect lies in the range 10^2 to 10^3 degrees Kelvin.

In the paper by **M. A. Krivolglaz**, "On the Theory of the Phonon Thermal Conductivity of Crystals," the phonon thermal conductivity of solid solutions at low temperatures (well below the Debye temperature) was discussed. It was proposed that the main mechanism of phonon scattering is scattering at concentrations of inhomogeneities in the crystal. In the low temperature region considered, long-wave acoustical vibrations are excited predominantly; as a consequence of this a macroscopic discussion of the problem is possible. A calculation was carried out in the elastic isotropic continuum approximation. For ideal solutions the thermal conductivity κ is inversely proportional to the product $c(1-c)$, where c is the concentration, and to the absolute temperature, T . The quantity κ depends strongly on the state of ordering of the solutions. A particularly strong effect of correlations in atomic positions in the solution on the phonon thermal conductivity should be observed in solutions of the critical compositions quenched from temperatures close to the critical temperature on the dissociation curve. The thermal conductivity of such solutions, measured at low temperatures, should be much smaller than that of ideal solutions. The thermal conductivity of a solution quenched at the critical point is proportional to the temperature and not to the inverse temperature, as occurs far from the critical point. The ratio of the thermal conductivities of a solution quenched from the critical point to the thermal conductivity of an ideal solution is equal in order of magnitude to $(kT)^2/(\hbar\omega_m)$, where ω_m is the maximum frequency of acoustical vibrations in the crystal; at low temperatures this ratio can be very small. A sharp decrease of the thermal conductivity associated with acoustical lattice vibrations should also take place at low temperatures close to the critical point on the curve of a second-order phase transition. In such crystals in a definite low temperature region optical vibrations of the lattice, the frequency of which can be two orders smaller than the usual frequency of optical vibrations, can also play an important part in the thermal conductivity.

A. I. Ansel'm and **V. M. Agranovich** pointed out in

the discussion the necessity of intensive study of the question of thermal conductivity in order to clarify the process of interference of the various scattering mechanisms and in order to provide effective formulae able to describe experiments.

In the paper by Yu. M. Popov and V. A. Chuenkov, "The Dependence of the Electron and Hole Mobilities in Germanium and Silicon on the Strength of the Electric Field at Low Temperatures," a calculation was made using the distribution function of electrons (holes) at low temperatures. The distribution function was obtained by solving the kinetic equation taking into account the effect of the external electric field, the scattering at lattice vibrations, and the scattering at charged impurities. It was shown that for some field $E = E_0$, the mobility has a maximum. Such a variation of mobility with field is related to the fact that as the strength of the electric field increases, the mean energy of electrons (holes) increases, and this in its turn causes the probability of scattering at charged impurities to decrease and the probability of scattering at lattice vibrations to increase. For $E < E_0$ the mobility is mainly determined by scattering at charged impurities; for $E > E_0$ scattering at charged impurities becomes unimportant.

In the paper by M. I. Iglitsyn, Yu. A. Kontsevoï and K. V. Temko, "A Calculation of the Recovery Time for Conduction in the Base Region of a Plane Junction," the results of calculating the recovery time for the conductivity of the base region of a plane p-n junction were communicated, taking into account the variation of carrier lifetime on injection level. The system of equations was solved by a numerical method on an electronic calculating machine. Several particular cases were considered, for which the stationary and nonstationary distributions of non-equilibrium charge carriers close to the p-n junction were found. A relationship was established between the recovery time and the lifetime of charge carriers for arbitrary injection levels. The calculation provides a basis for the widespread method of experimentally studying the variation of lifetime on injection level.

A problem in the theory of p-n junctions was also the subject of a paper by É. I. Adirovich and E. M. Kuznetsova, "Capacity and Electrical Breakdown of p-n Junctions." The existing theory of p-n junctions is based on the idea of a quasi-dielectric depletion layer which occurs in the region of the p-n junction for inverse voltages exceeding several kT/q . Meanwhile, the starting assumption on the depleted state of the p-n junction ($p \ll N$; $n \ll N$, where N is the surplus concentration of the dominating impurity) does not correspond to the true picture of the distribution of charge carriers in p-n junctions.

The calculation carried out showed that the depleted state of a p-n junction is attained for inverse voltages $|V| \gtrsim (kT/q)(N_a/N_d)$ where N_a and N_d are the concentrations of acceptors and donors, respectively, in the

p- and n-type regions. For inverse voltages $|V| \ll (kT/q)(N_a/N_d)$ the maximum value of the field strength in the p-n junction is practically the same as the thermodynamic equilibrium value, and the so-called charge capacitance of a p-n junction is several orders smaller than the value given by the Schottky-Mott formula. The physical cause for the results obtained is the existence of an inversion layer ($p > N$) in the n-type semiconductor, which is simultaneously a high resistance region and a region of high field strength. Due to the high concentration of holes and the large density of space charge in the inversion layer, the picture of field distribution and charge carrier concentration in a p-n junction is essentially different from the picture of a depleted layer, and the results coincide with formulae from the Schottky-Mott theory only for large inverse voltages $V \sim kT/q \ln N_a/N_d$, which destroy the inversion layer. The reactive properties of a p-n junction are due to two effects caused by the change of voltage: 1) the diffusion of minority carriers injected into the quasi-neutral region; 2) the readjustment of the space charge region. The first of these effects is related in the theory to a diffusive and the second to a charge (intrinsic) capacity of a p-n junction. The analysis shows the incorrectness of determining the intrinsic capacitance $C = -dQ/dV$ and leads to the formula $C = q(d/dV) \int n dx$. The range of applicability of the Schottky-Mott formula for the capacity is given by the inequality

$$V \lesssim \frac{kT}{q} \ln \frac{N_d^2}{10n_i^2}$$

It has now been experimentally established that electrical breakdown of semiconductors (with the exception of very sharp p-n junctions) occurs due to impact ionization by electrons (or holes). A discussion of this problem from the theoretical viewpoint was given in the paper by V. A. Chuenkov, "The Theory of Electrical Breakdown in Semiconductors." By solving the kinetic equation the distribution function of electrons (holes) in a strong electric field was obtained. With its help it was shown that, as the strength of the electric field increases, the mean number of ionizations (by one electron) in unit time increases, but the mean number of recombinations falls. Thus, at some critical value of the electric field strength $E = E_c$, the kinetic equation ceases to have a stationary solution (the concentrations of electrons and holes tend to infinity) and electrical breakdown of the semiconductor takes place. In a p-n junction recombination plays no part (the drift time of an electron through the junction is much less than the lifetime), and the process balancing impact ionization is the drift of electrons out of the p-n junction region. It was shown that the breakdown criterion in not-too-sharp p-n junctions is the Townsend criterion for gases. Using the distribution function found for the electrons (and holes) in the p-n junction, the variation of the coefficient of impact

ionization on electric field strength and temperature was obtained.

The phenomenon of impact ionization was also considered in the paper by L. V. Keldysh, "The Kinetic Theory of Impact Ionization in Semiconductors." The effect of impact-ionization processes on the distribution function for electrons and holes in a strong electric field was investigated. It was shown that the energy variation of the impact ionization probability close to the threshold is quite different for crystals with small and large dielectric constants, and the solution of the kinetic equation in both these cases was discussed. Expressions were obtained for the equilibrium number of carriers in strong field, the coefficient of impact ionization, the critical field, etc. The variation of breakdown field on the temperature, on the specimen thickness, and on the law of interaction of electrons with the lattice were found. A relationship was established between the expressions obtained and the known breakdown criteria of Fröhlich and Hipel. It was shown that an increase of electric field causes a decrease in the recombination velocity, as a result of which the equilibrium number of carriers starts to grow as the field increases, long before impact ionization sets in.

The paper by G. V. Gordeev, "Impact Ionization in the p-n Junction," was also devoted to the problems of impact ionization. The current multiplication factor due to impact ionization in a p-n junction was treated (the multiplication coefficient is the ratio of the current density j at the given voltage to the saturation current density j_s). McKay and Miller⁸ determined the variation of ionization rate for electrons and holes from the field required to give a known current multiplication or the breakdown voltage. Here the inverse problem is posed. A formula was obtained for the multiplication coefficient in the case of sharp breakdown. The limits of its applicability were studied.

A. Yu. Leïderman and P. M. Karageorgii-Alkalaev, in their paper, "On the Application of a Semiconductor Model with a Single Impurity Level to the Explanation of Photo-Conductivity and Photoactivation Quenching Effects," considered the negative photoeffect in semiconductors. Two mechanisms of the photoeffect were studied: excitonic and electronic. In the first case the process is inertialess. Since the lifetime of the exciton is different from zero, the growth of free carrier concentration is delayed. The condition for a negative photoeffect to occur in this case leads to two temperature limits. In the electronic mechanism, light excites electrons from the valence band into the impurity level. Thus, a hole is formed in the valence band. An electron from the conduction band recombines with this hole, as a result of which the number of free carriers decreases — a negative photoeffect occurs. A characteristic feature is the inertialessness and also the existence of a lower temperature limit. The theory can provide a qualitative explanation of the experimental data.

A group of papers dealt with the energy band diagram for carriers in particular types of crystalline lattice. The band structure of A_3B_5 -type semiconductors was discussed in the paper by A. I. Gubanov and A. A. Nran'yan, "A Study of the Energy Spectrum in Semiconductors with the Sphalerite Structure." Using the equivalent orbital method, analytic expressions were obtained for the dependence of energy on wave vector for the four valence bands and the four conduction bands in A_3B_5 -type compounds.

The results obtained were analyzed to establish the band structure features applicable to all A_3B_5 compounds. It was established that in changing from elements of Group IV to an A_3B_5 compound an additional forbidden band arises both inside the four valence bands and inside the four conduction bands, which separates three of the bands from the fourth.

The paper by K. D. Tovstyuk and I. V. Gvozdovskii, "The Energy Spectra of Charge Carriers in Crystals with the Zinc-blende Structure," treated the energy spectrum of polar excitations in crystals with the zinc-blende structure using the many-electron model proposed in reference 9, which takes into account the character of the bonds. A parameter introduced to describe the degree of asymmetry of the electron cloud localized in the bond is involved in the spectrum. The presence of this parameter increases the effective mass of the quasi-particles (charge carriers) and the width of the forbidden gap.

In V. A. Chaldyshev's paper, "The Structure of the Energy Spectrum in Crystals with the Chalcopyrite Structure," the topological structure of the energy spectrum in crystals with the chalcopyrite type lattice ($CuFeS_2$) was studied. The calculation was carried through using a method proposed by Buchhardt, Smoluchowski, and Wigner. The characters of the irreducible representations of the simple and binary symmetry groups in such crystals were obtained. The character of the contact of energy bands was analysed and the problem of the effect of spin-orbit interaction was discussed. Also studied was the variation of $E(k)$ under various assumptions on the position of the band edges.

"The Use of the Method of Equivalent Orbitals to Calculate the Valence Band of Certain Covalent Crystals" — a paper by E. I. Cheglov — consisted of a discussion, using group theory and the method of equivalent orbitals, of the valence band structure of covalent crystals of the tellurium and bismuth types. The valence band of tellurium-type crystals was found to consist of three bands. The maximum of the valence band can be situated at one of the points Γ , A, K, I (in the notation of reference 10) in the Brillouin zone. At whichever of the points mentioned the maximum is situated, the bands do not touch at the extremities, and thus, in tellurium type crystals, one type of hole should be observed. The surfaces of constant energy near the maximum will be ellipsoids of rotation around the principal axis of the crystal. For bismuth-type crystals, both with and without account of spin-orbit inter-

actions, the extrema of the function $E(k)$ follow from the symmetry of the crystal and are situated at the center of the Brillouin zone and at the centers of the faces at the zone surfaces. When spin-orbit interaction is neglected, contact of two bands is possible at certain points in the Brillouin zone. Taking spin-orbit interaction into account removes this degeneracy. All bands become simple bands. Under certain conditions applicable to the interaction constants of second and third neighbors, the valence band maximum will be situated at the center of the Brillouin zone. The surfaces of constant energy close to the maximum will be ellipsoids of rotation about the trigonal axis of the crystal. The symmetry of the wave functions of valence band states was found.

In the paper by G. E. Pikus and G. L. Bir, "The Effect of Deformation on the Energy Spectrum and Electrical Properties of p-type Germanium and Silicon," an expression was obtained for the spectrum of holes in the deformed crystal. From the general formula, limiting expressions for the energy were obtained, one of which was applicable at sufficient distance from the band edge and the other was applicable at the band edge. From these formulae it follows that, whilst at high temperatures piezo-resistance effects are proportional to the deformation and are relatively small, at sufficiently low temperatures the electrical properties of the deformed crystal become markedly anisotropic; the degree of anisotropy does not depend in general on the magnitude of the deformation, but is determined only by its direction. A. I. Ansel'm pointed out the great value of the work presented in the paper. The study of the effect of deformation on the electrical properties of semiconductors can give important insight into their band structure.

Much attention was paid at the Conference to the theory of impurity centers, their luminescence and the calculation of recombination due to various centers in a crystal. In the paper by A. I. Mirtskhulav, "The Determination of the Recombination Coefficients of Various Centers in a Crystal," a calculation of the recombination coefficients of defects in a crystal was made using a stochastic method. The random motion of particles in a crystalline lattice on which is superposed a certain ordered motion caused by the field of a recombination center $V(r)$ was considered. Each recombination center is surrounded by an ideally absorbing spherical surface of radius R and it is required to find the probability that, after N displacements of the particle, it find itself for the first time at the absorbing spherical surface mentioned.

The following expression was obtained for the recombination coefficient

$$\beta = 4\pi D \left(\frac{a}{1 - e^{-a/R}} + \frac{R^2}{\sqrt{\pi D t}} \right),$$

where D is the diffusion coefficient, $a = e^2/\epsilon kT$ (ϵ is the dielectric constant) for $R \rightarrow 0$

$$\beta = 4\pi Da,$$

which agrees with the results of S. I. Pekar.¹¹ The radius of the ideally absorbing sphere which is involved has a quite definite physical meaning. In the case of recombination of an electron with a hole, R is the radius of the valence-electron orbit. In the case of recombination of vacancies of opposite signs or of a vacancy and an interstitial ion, the radius R is equal in order of magnitude to the interatomic distance (then it is impossible to neglect the second term in the formula for β ; taking it into account gives a variation of β on time for the initial stage of the recombination of non-equilibrium centers). To generalize the results obtained to the case of mobile recombination centers it is sufficient to replace D by $D_1 + D_2$, where D_1 and D_2 are the diffusion coefficients of the recombining particles.

In the discussion, A. I. Gubanov expressed doubt on the applicability of the calculation to the recombination of electrons and holes, because quantum effects play an important part here. As V. L. Bonch-Bruevich remarked, to calculate this when using the theory described and when quantum effects must be taken into account, it is necessary to compare the times τ_{diff} and τ_{recomb} .

S. I. Pekar pointed out that the recombination coefficient β should, by definition, not depend explicitly on time. Perhaps, as the author himself pointed out, the results were true in the limiting case of large values of t , and one should, therefore, allow t to tend to infinity. Then the second term in the expression for β disappears and the result agrees with the results obtained in reference 11.

In the paper by A. M. Ratner and G. I. Zil'berman, "On the Theory of Luminescence from Impurity Centers," were presented the results of calculations on the spectral variation of the absorption coefficient and emitted light intensity for phosphors containing luminescent impurity centers. The displacement by absorption of the equilibrium of lattice ions in the electronic transition and the change of frequency of lattice oscillations were both taken into account. It was shown that the change of lattice oscillation frequencies in the electronic transition is responsible for the departure of the absorption and luminescence spectra from mirror symmetry, so that neglect of the change of frequencies is permissible only in the case when the "law of mirror symmetry" is obeyed. A relationship was established between the departure of the absorption and luminescence spectra from mirror symmetry and their departure from the Gaussian shapes. Both these effects are associated with the change of frequencies in the electronic transition. A relationship was obtained which directly relates the absorption and luminescence spectra; from this relationship Stokes' law follows. The probability of a radiationless transition between discrete energy levels of the crystal due to the presence

of an impurity center was calculated. A relationship was shown between the probability of temperature quenching of luminescence and the form of the luminescence spectrum. The variation of the activation energy for radiationless (thermal) transitions on the asymmetry of the absorption and luminescence spectra was studied. A qualitative comparison of theory with experiment was made. Using the results obtained tentative qualitative conclusions were drawn on the mechanism by which energy is transferred from the lattice to impurity atoms when the crystal is excited by hard radiation or ultraviolet light in the intrinsic absorption band of the crystal.

Problems in the theory of luminescent centers in alkali-halide crystal phosphors were considered in the paper by **I. N. Kristofel**, "A Quantum Mechanical Calculation of the Adiabatic Potentials and Spectra of the Luminescent Center in KCl-Tl." The luminescent centers in alkali-halide crystal phosphors have small effective radii. A model of the center is used in which the activator ion replaces a cation of the host at a lattice site. The activator interacts with the local oscillations. The number of ions involved in the center is determined by the number of ions which participate in the local oscillations. Proceeding from the non-relativistic Hamiltonian of the entire crystal, equations were obtained in the adiabatic approximation which determine the one-electron wave functions of the ions involved in the center. As zero-order approximation, radial wave functions were determined by the method used in reference 11, taking into account the deforming effect of the field of the point lattice. The fact that the ions are not points was considered as a perturbation. Expressions were obtained for the energy of the activator in the lattice and for the adiabatic potential. In the alkali-halide crystal phosphors the activator interacts more strongly with the fully symmetrical than with the other local oscillations. Therefore it is possible to use in the first approximation the so-called single oscillator approximation. As a concrete case, the 1S_0 and 3P_1 states of the luminescent center in KCl-Tl were considered. It was found that on introducing Tl^+ in the ground state into the KCl lattice it pushed the surrounding ions apart somewhat, but in the excited state on the other hand it pulled them together. The energy of replacing K^+ in the KCl lattice by Tl^+ in the ground state is ~ 0.43 eV. The frequency of the fully symmetrical oscillation in both states is smaller than the limiting frequency of the optical vibrations of pure KCl. Expressions were obtained for the adiabatic potentials of the 1S_0 and 3P_1 states of the luminescent center in KCl-Tl and for the absorption and emission spectra. Agreement between theory and experiment is good.

In the paper by **Yu. É. Perlin**, "The Consideration of the Polaron Effect in the Theory of Multi-phonon Ionization of Impurity Centers," the thermal ionization of the F-center was discussed. The fact that the proc-

ess of ionization with transition into a polar state is more probable than the formation of a free electron was taken into account. To discuss such transitions a transformation is made to the variables of the adiabatic lattice Hamiltonian in Pekar's polaron theory, which corresponds to a localized state of the electron. The approximate wave function of the transformed Hamiltonian was obtained by a straightforward variational method. The Bethe-Sommerfeld potential

$$V(r) = -(\mathbf{u}(r), \nabla\omega),$$

was chosen as the operator for the multi-phonon radiationless transition; where \mathbf{u} is the displacement of the continuum which gives rise to the longitudinal acoustic wave. A formula was obtained for the probability of radiationless ionization. It was possible to establish a relationship between the probability of thermal ionization and the mean equilibrium value of the effective capture diameter at a given local level in multi-phonon transitions.

In the paper by **K. K. Rebane**, "The Relationship Between Recombination Luminescence and Conductivity in Crystal Phosphors," it was shown how to obtain in the usual band pictures of homogeneous crystal phosphors an accurate theoretical relationship between the recombination luminescence and the conductivity (the concentration of free carriers). To obtain this relation it is sufficient to consider the basic equation of recombination, i.e., the equation which directly describes the recombination which gives rise to luminescence. Formulae were obtained for a number of possible types of recombination equations, in the case of both isothermal and non-isothermal relaxation processes. In particular, the model was discussed in which purely electronic (hole) conduction takes place, and the luminescence arises during the recombination of electrons at hole capture levels of only one sort. The formulae relating the recombination luminescence and the conductivity are useful in three respects: a) they can provide a criterion for the conformity of the basic recombination equation to the real process; b) if the formulae are satisfied for some values of the parameters entering into them, these parameters are thereby determined for the object under consideration; c) they can provide additional criteria for the accuracy of the theoretical relaxation curves obtained from any system of kinetic equations containing the basic recombination equation of the forms under consideration.

The paper by **V. M. Buřmistrov** and **V. N. Piskovoř**, "An Investigation of the Accuracy of the Variational Method in the Problem of the Impurity Absorption in Silicon Crystals," was devoted to an evaluation of the accuracy of the variational method in a strictly mathematical manner. In the papers given in reference 13, a method of evaluating the accuracy of the approximate eigenvalues of the linear self-adjoint operator is given, as well as the mean values of functions of the system coordinates and the intensity of the transitions. In the

work reported, these results were used to evaluate the accuracy of the energy terms — calculated by the direct variational method — of the optical electron of a Group V impurity atom in silicon and germanium, where the Hamiltonian of the optical electron is written in the effective mass approximation. It was shown that by using a knowledge of the accurate solutions of the problem in the limiting "hydrogen-like" and adiabatic cases, it was possible to obtain an upper limit for the error in the approximate values of the energy terms which does not exceed several percent.

The results of a study of TiO_2 containing a paramagnetic impurity (Fe^{3+}) were given in the paper by **M. M. Zaripov**, **V. M. Vinokurov** and **V. G. Stepanov**, "Paramagnetic Resonance in Rutile Single Crystals." The paramagnetic resonance spectrum was observed at room temperature at a wavelength ~ 3.2 cm. The number of observed resonance absorption lines depended strongly on the direction of the constant magnetic field relative to the optical axis of the crystal. An analysis of the spectrum showed that the spectrum was caused by the ion Fe^{3+} , which replaces Ti^{4+} isomorphously in the rutile lattice. To interpret the spectrum the spin-Hamiltonian was constructed and its parameters were found.

Apart from the papers briefly described above, which were included in the program of the Conference, a large number of papers were presented outside the program (by decision of the Organizing Committee). The corresponding manuscripts in printed form were distributed to the Conference participants for discussion.

The afternoons were devoted to seminars convened at the initiative of individual groups.

In a number of the papers presented outside the program problems in the many-electron theory of solids were treated. The theory of elementary excitations in atomic semiconductors with two valence electrons on each atom was developed in the paper by **A. G. Samoïlovich** and **S. L. Korolyuk**. In the paper by **S. V. Vonsovskii** and **M. Sh. Giterman**, the many-electron treatment of ionic crystals was considered; the general theory was applied to the electrical conductivity of antiferromagnetic polar crystals, and to the variation of the semiconductor parameters on the impurity concentration. A calculation on the magneto-resistance of semiconductors with spin-saturated ground state, using a new form of the polar model of a crystal, was carried out by **I. V. Stasyuk**. For strong magnetic fields, a practically linear variation of resistance on magnetic field strength was obtained, but for weak fields the variation was quadratic. The calculation of the contribution of Frenkel excitons to the magnetic susceptibility of semiconductors was made on the basis of the same theory by **V. V. Vladimirov**. It was shown that under some conditions the existence of a large paramagnetism due to excitons is possible. **A. E. Glauberman** and **I. T. Tsymburskaya** considered the

character of the chemical bond in the magneto-resistance theory of germanium-like semiconductors. **K. B. Tolpygo** made a theoretical investigation of the properties of crystals not completely polar.

The structure of the energy spectrum of carriers was investigated in several papers. **A. I. Gubanov** and **F. N. Gashimzade** studied the band structure of semiconductors of the CdInSe_4 type using group theory. **K. Ya. Shtivel'man** studied the energy spectrum of holes in crystals with the diamond structure on the basis of the many-electron theory; it is essential to introduce into the picture spin-orbital interaction. The contact of energy bands in crystals was discussed by **O. V. Kovalev** and **T. Ya. Lyubarskii**; they studied the degeneracy associated with spatial symmetry and symmetry with respect to time inversion. **E. K. Kudinov**, using a many-electron approach, calculated the energy spectrum of holes in Bi_2Te_3 , taking into account the character of the bonds. **É. I. Rashba** and **V. I. Sheka** made a group-theoretical investigation of the band structure of semi-conductors.

Optical phenomena were studied in a series of papers. The optical properties of semiconductors in the infrared region were treated by **V. I. Cherepanov**. Optical absorption by excitons in cuprous oxide in the absence of external static fields was investigated by **S. A. Moskalenko**; the hydrogenlike series of sharp absorption bands observed in cuprous oxide on the long wavelength side of the intrinsic absorption, is due to the occurrence of Wannier-Mott exciton states with quasi-momentum close to zero. **A. A. Vorob'ev** studied the relation between the additional absorption and the chemical composition of alkali-halide crystals. **I. V. Abarenkov** studied the properties of F centers with the help of an effective potential method: the position of the maximum of the F-band absorption and its variation with hydrostatic compression. **L. É. Gurevich** and **I. P. Ipatova** treated the Faraday effect of free carriers in semiconductors. The eigenvalues and eigenfunctions of a conduction electron with anisotropic mass in a strong magnetic field were obtained. The interaction with light was treated by a quasi-stationary method without taking collisions into account.

Several papers were devoted to the study of photo- and thermoelectric phenomena in semiconductors. In the paper by **I. D. Potekhina**, which dealt with relaxation processes in phototransistors, the relaxation of the potential difference between emitter and base and the relaxation of the collector current, when illumination is commenced and when it is cut off, were calculated.

In the paper by **V. E. Khartsiev**, the kinetics were considered of optically and thermally stimulated phenomena consisting of conductivity changes in a semiconductor containing trapping centers when it is heated by various types of illumination. **E. N. Agafonova** and **A. A. Yakub** studied the effect of anisotropy in the energy spectra of an atomic semiconductor on the thermal emf due to radiation. The thermal emf was calculated

on the assumption that the surface of constant energy for the electrons can be approximated by an ellipsoid of rotation. The results of experimental studies of the change in the photoelectric properties of zinc selenide layers as a function of their structure were given in a paper by **G. A. Zholkevich**. The effect of thermoelectric forces on the skin-effect in metals was treated by **M. I. Kaganov** and **V. M. Tsukernik**.

Much consideration was given to the kinetics of non-equilibrium processes in semiconductors. **A. D. Chevychelov** considered the voltage-current characteristic of a p-n junction, taking into account the recombination of electrons and holes in the transition layer.

A. G. Samoïlovich and **M. I. Klinger** applied the general expression for the nonequilibrium distribution function to the important case of anisotropic weak electron-phonon scattering with anisotropic energy spectra for electrons and phonons. An expression was obtained for the tensor relaxation time in the anisotropic crystal Bi_2Te_3 . **B. Ya. Yurkov** calculated the range-energy relationship for atoms of the crystalline lattice of silicon knocked on during irradiation of the crystal by electrons. **E. P. Pokatilov** treated the resonance of charge carriers in an ultrasonic wave by calculating the interaction of charge carriers in a magnetic field with the electric field created by the ultrasonic wave. **V. A. Kovarskiĭ** investigated the dependence of thermal electronic transitions in semiconductors on the electron-phonon coupling constant. The role of two-phonon processes in conduction-electron scattering in ionic crystals was considered in the paper by **I. G. Lang**. The relaxation time for conduction electrons in ionic crystals associated with two-phonon scattering at optical lattice vibrations was determined. **L. É. Gurevich** and **G. A. Roman** calculated the thermal conductivity of ferromagnetic semiconductors at low temperatures, taking into account the scattering of phonons and magnons by defects of the lattice and by one another. **B. Ya. Moïzhes** evaluated the transfer of heat by electromagnetic radiation in uniaxial crystals. The theory developed was related to the experimental results of **E. D. Devyatkova** and **I. A. Smirnov**. The electrical conductivity of magnetite at low temperatures was investigated by **N. P. Kontorovich** and **Yu. P. Irkhin**. **A. G. Samoïlovich** and **V. M. Nitsovich** considered the effect of correlations between the electrons on the electrical properties of semiconductors with a narrow impurity band. Satisfactory agreement with experimental data was obtained for germanium. **V. P. Shabanskiĭ** studied non-equilibrium processes in impurity semiconductors. Using the kinetic equations for impurity semiconductors, an explicit form for the kinetic coefficients was obtained. **V. G. Skobov** calculated the conductivity of semiconductors at low temperatures in a strong magnetic field, involving the scattering of electrons at neutral impurities and at lattice defects. **F. G. Bass** and **M. I. Kaganov** developed the theory of galvanomagnetic phenomena on the basis of the classical kinetic

equations under the condition $\mu H \ll kT$. **I. M. Tsidil'kovskiĭ** and **V. P. Shirokovskiĭ** considered galvanomagnetic and thermomagnetic phenomena in n and p-type germanium, taking into account the peculiarities of the energy spectrum of charge carriers and using the kinetic equation. In the contribution by **S. M. Ryvkin**, **Yu. L. Ivanov**, **A. A. Grinberg**, **S. R. Novikov** and **N. D. Potekhina**, the results were presented of an investigation of the concentration distribution of minority carriers in a magnetic field, and data was given on the longitudinal magneto-concentration effect in a longitudinal magnetic field.

In the seminar on the magnetic properties of solids, papers were read by **V. L. Gurevich** ["The Absorption of Ultrasonics in Metals in a Magnetic Field"], **A. M. Kosevich** and **V. V. Andreev**, ["On the Collision Integral in the Quantum Kinetic Equation"], **K. B. Vlasov** and **B. Kh. Ishmukhametov** ["On the Rotation of the Plane of Polarization of Elastic Waves in Magnetically Polarized Magneto-Elastic Media"], and **E. A. Turov** ["On the Theory of Weak Ferromagnetism"].

The seminar on the theory of p-n junctions in semiconductors was devoted to the discussion of the following questions:

1) the calculation of the static voltage-current characteristic of a p-n junction at high injection levels; the basic principles governing the current through a p-n junction when there is a change of the diffusion length (a paper by **V. I. Stafeev**).

2) the refinement of the calculated static voltage-current characteristic of a p-n junction when recombination is present in the space-charged region (a paper by **V. I. Stafeev** and **B. V. Tsarenkov**).

3) the inclusion of the space-charge of mobile carriers when considering electrical breakdown of a markedly asymmetrical p-n junction (a paper by **A. I. Uvarov**).

In the seminar on the mechanism of luminescence and electrical conductivity in ionic crystals, **Ch. B. Lushchik** gave a paper "On the Mechanism of Luminescence in Alkali-Halide Crystal Phosphors", and **P. V. Meĭklyar** and **V. V. Gladkovskiĭ** contributed a paper "The Dark Conductivity of Silver Bromide and its Change after Illumination."

In the seminar devoted to quantum Green functions in statistical physics, papers were read by: **V. L. Bonch-Bruevich** and **Sh. M. Kogan** ["On the Theory of Temperature Quantum Green Functions"], and by **N. N. Bogolyubov** and **S. V. Tyablikov** ["Retarded and Advanced Green Functions in Statistical Physics"].

Seminars also took place on the interactions of different forms of radiation with semiconducting materials, on semiconductors with charge carriers of small mobility, and on band structure in various semiconductors.

The Conference showed the significant increase in theoretical work on semiconductors and the marked strengthening in the ranks of theoreticians working in

this field, mostly due to young scientists. The majority of contributions to the Conference were of a high level and of great scientific interest.

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