Meetings and Conferences

FOURTH CONFERENCE ON SEMICONDUCTOR THEORY

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THE Fourth All-Union Conference on Semiconductor Theory, which met in Tbilisi on October 17 — 22, 1960, had been convened jointly by the Committee on Semiconductors of the U.S.S.R. Academy of Sciences, the Georgian Academy of Sciences, and the Tbilisi (Stalin) University. Over 250 specialists from 25 cities of the Soviet Union participated. More than 80 papers, followed by lively discussions, were read at the plenary and sectional sessions, in addition to the seminars on individual topics.

S. I. Pekar, chairman of the organizing committee, devoted his opening address to the memory of Academician Abram Fedorovich Ioffe, the recently deceased great scientist and organizer of Soviet physics, who was especially responsible for much of the development of semiconductor physics in the Soviet Union. Academician **É. L. Andronikashvili** of the Georgian Academy of Sciences described the outstanding part played by Ioffe in the establishment of numerous physics and physico-technical institutes in many cities of the Soviet Union, and in training the great galaxy of talented scientists who are now in the forefront of Soviet physics. He emphasized the enormous range of Ioffe's scientific interests, and his remarkable scientific intuition, which enabled him to discern correctly the most promising directions of scientific progress.

Preceding the presentation of original work, **K. B. Tolpygo, A. I. Gubanov, G. G. Taluts**, and **V. A. Myamlin** reviewed the most interesting foreign papers presented at the Prague Conference on Semiconductors. About 600 persons, representing 25 countries, participated in the International Conference on Semiconductor Physics, held in Prague from August 29 to September 2, 1960. About 200 papers were delivered at 21 sectional sessions. About 40 communications were discussed "reportorially" in five discussion groups. Two plenary sessions heard **A. F. Ioffe** speak on "New Paths of Semiconductor Investigations," **W. Shockley** on "Problems of p-n Junctions in Silicon," and the concluding summing-up address by Dr. J. Tauc of the Czechoslovak Republic. Shockley discussed the factors causing large reverse currents in silicon p-n junctions — impact ionization requiring energy above 1.1 ev (with momentum conservation ensured by phonons), appreciable nonuniformity in the distributions of impurities and SiO_2 with the resulting higher local fields, microplasma formation in different places, etc. The theory agrees semi-quantitatively with the observed regularities.

The central topics of the conference were the problems concerning the energy structure of specific semiconductors — how to determine the forms of electron and hole bands and the effective masses of carriers, and secondly the spectra of excitons, impurities and electron surface states as well as phonon states. For these purposes use has been made of cyclotron and paramagnetic resonances, various optical and magneto-optical measurements, studies of electroluminescence, etc., combined with theoretical work. The two groups of theoretical papers treated 1) the basis of the single-electron approximation and the development of methods for calculating band structures, and 2) the construction of theories for different effects using band concepts, with band parameters determined experimentally.

In a review paper **W. Kohn** (USA) summarized results obtained in studies considering electrons and holes as quasi-particles obeying a definite dispersion law, with Coulomb interactions involving the dielectric constant ϵ. Among the principal achievements were Pratt's nonlocal potential method, the introduction of a repulsive potential instead of an orthogonality condition, an adiabatic treatment of the motion of a band electron, and a theory of polarons.

F. Herman (USA) reported on the calculation of electron band states using computers (with up to 4×10^6 operations per second). **N. Pincherle** and **P. Lee** (England) and **J. Della Riccia** (France) presented band calculations for rectangular potential wells in a three-dimensional lattice, and for Mg_2Sn and Mg_2Ge using atomic potentials. **F. Quell** (USA) reported band calculations by the OPW and APW methods, with a repulsive potential replacing the orthogonality condition and using the Pratt nonlocal potential for electron interaction. **J. Phillips** (England) investigated the electron charge density distribution along the (111) direction of covalent and ionic crystals of Si, Ge, and BN for valence and conduction band states as a function of the wave vector **k**. Some theoretical and experimental papers were concerned with semiconductor absorption at the edge of the first fundamental band. **F. Stern** (USA) computed the intensities of direct optical transitions in InAs and InSb using the Kane theory; from a comparison of theory with experiment he calculated 0.024 m as the effective electron mass in InAs and 0.4 m as the heavy hole mass in InSb. **P. Elliot** (England) proposed a theory of indirect transitions in a simple band scheme. Its agreement with experiments in Cu_2O was demon-

strated by **S. Nikitine** (France). It was thus possible to establish the nature of transitions at "steps" on the absorption curve and of lines of the yellow exciton series. **A. Haug** (West Germany) proposed an exciton theory based on the HLH (Heitler-London-Heisenberg) method, incorporating the models of Frenkel', Wannier and Heller-Marks (but without substantiating the dielectric constant for electron-hole interaction). W. **Choyke** and **L. Patrick** (USA) investigated the fine structure of the absorption edge in SiC (6H type) and established the existence of excitons in this crystal, optical transitions being accompanied by the emission or absorption of different phonons. **J. Dixon** (USA) investigated a broader absorption spectrum of InAs for large impurity concentrations, and found nonparabolic dependence $E(\mathbf{k})$ of energy on the wave vector.

Several papers reported investigations of infrared absorption by free carriers, from which effective masses were estimated. This was done by **J. Dixon** for InAs and by **L. Huldt** (Sweden) for Si. The latter made ingenious use of photocarriers created by modulated light; absorption by these carriers was distinguished unambiguously. **M. Cardon** (Switzerland) evaluated effective masses in InSb, InP, GaSb, and GeAs from the dependence of crystal polarization on free-carrier concentration. **J. Haynes, M. Lax** and **W. Flood** (USA) interpreted the fine structure of recombination emission in silicon during the passage of current through a p-n junction. The different peaks were interpreted as representing combinations of interband and exciton transitions involving different phonons, as well as impurity levels.

A considerable number of papers dealt with the magneto-optical properties of semiconductors. These included the study of infrared cyclotron resonance in InSb, by **E. Palik, G. Picus, S. Teitler,** and **R. Wallis** (USA) the Faraday effect in InSe and InP, by **E. Moss** and **A. Walton** (England), ellipticity associated with the Faraday effect in InSb, by **S. Smith** and **U. Pidgeon** (England), the Zeeman effect for exciton absorption, etc. **B. Lax** presented an especially interesting review paper. In addition to the foregoing effects, he discussed the magneto-plasma effect and the magneto-tunnel effect (the dependence of the Zener current on the magnetic field). We must also mention the experimental discovery of holes with negative effective mass in Ge using cyclotron resonance, by **G. Dousmanis** (USA), and the theory of cyclotron resonance for these holes, proposed by **B. Rosenblum** and **R. Duncan** (USA).

G. Feher (USA) reviewed the paramagnetic resonance of donors in Ge, Si, and InSb. He discussed the splitting of absorption lines by interactions between electron and nuclear spins, the degeneracy of donor levels resulting from the existence of several energy minima, the effect of crystal deformation on the paramagnetic absorption spectrum, and particularly the changes $\Delta g_{\parallel}$ and $\Delta g_{\perp}$ of the g factor of spin-lattice relaxation. Paramagnetic resonance involving conduction electrons and spin-lattice relaxation were investigated by **G. Lancaster** and **E. Schneider** (England). Over a broad temperature range $T_r/T_s \sim 0.25\,(\Delta g)^2$, in agreement with Elliott's theory (T_s is the relaxation time and T_r is the mean free electron time). A theory of spin-lattice relaxation was proposed by **Laura Roth** (USA), based on an extension of the deformation potential method.

Among the many papers concerned with defects in ionic crystals the most interesting was that of **W. Känzig** (USA), who proved that paramagnetic resonance in alkali halide crystals with excess holes results from the autolocalization of holes on the two nearest halide ions in an ideal crystal. This system possesses a negligible diffusion coefficient due to the large effective mass associated with crystal deformation. **H. Rabin** and **J. Schulman** (USA) determined the fine structure (three peaks) of the F band of CsCl and CsBr. **A. Halperin** et al. (Israel) investigated the disappearance rates of different color centers in alkali halides as they are heated. They showed, in particular, that the so-called K band is not associated with excited F-center states.

Four sessions of the conference were devoted to the important topic of transport phenomena. **C. Herring** (USA) mentioned three possible approaches to the treatment of transport phenomena — density matrices, kinetic equations, and jumps (for crystals with low mobilities). He mentioned the nullification of two-phonon scattering when a perturbation method is used consistently; this had been overlooked by earlier investigators. He also discussed the methods of deformed orthogonal functions, the unsatisfactory state of the theory of impurity scattering and a number of other difficulties in the theory. **H. Ehrenreich** (USA) proposed a theory of mobility in n-type GaAs, to include the Hall effect and the pressure dependence of mobility. The theory takes into account both lattice and impurity scattering, using data on the band structure, and contains no free parameters. Besides scattering theory, related papers treated the problems of hot electrons, galvanomagnetic effects etc.

The agenda of the conference included surface states, recombination, photoconductivity, radiation defects, properties of semiconductor compounds, tunnel diodes etc.

1. OPTICAL PROPERTIES OF SEMICONDUCTORS

The largest number of papers were devoted to the investigation of the optical properties of semiconductors — the theory of exciton absorption, space dispersion, additional light waves, exciton scattering etc.

S. I. Pekar, M. S. Brodin and **B. E. Tsekvava**: "The Optical Anisotropy of Cubic Crystals, Additional Light Waves in Crystals, and their Experimental Detection." A consistent theory was developed for the propagation

of light waves in cubic crystals with spatial dispersion, taking into account both crystal anisotropy and the creation of additional waves.[1] The frequency dependence of refractive indices was derived for waves propagating along symmetry axes; qualitative differences were found for exciton zones with different symmetry. Absorption polarization was determined, depending on the symmetry of the exciton state. A comparison with the data obtained by E. F. Gross and A. A. Kaplyanskii[2] on the polarization of the n = 1 line in the yellow series of Cu_2O assigns Γ_{25}' symmetry to the line. Near this absorption line the theory predicts the existence or absence of additional waves and the associated oscillations of the transmission coefficient for varying crystal thickness, depending on the direction of propagation and polarization. This agrees with the data obtained by I. S. Gorban' and V. B. Timofeev.[3] Oscillations of this character were previously observed in anthracene.[4]

In the discussion **V. M. Agranovich** expressed the following opinions: 1) in Pekar's theory the mean microfield was unjustifiably replaced by the macrofield of the electromagnetic wave; 2) the conclusion regarding the possibility of additional waves was based on a theory that is valid in the absence of absorption, but the comparison with experiment is carried out in a region of considerable absorption; 3) Brodin's experiments do not prove the existence of additional light waves, since in the presence of spatial dispersion the induction vectors of the fundamental waves are not mutually perpendicular and interference is possible. **Pekar** replied that: 1) the macrofield differs appreciably from the mean microfield only when the wave length is of the order of the lattice constant, and is unimportant for the effects considered; 2) all conclusions of the theory are based on formulas taking absorption into account; 3) in Brodin's experiments the propagation direction and polarization of light were such that the anthracene monoclinic axis remained the principal axis of polarization, even with spatial dispersion taken into account.

R. F. Kazarinov and **O. V. Konstantinov**: "The Doppler Shifts of Exciton Absorption Lines." A theory of large-radius excitons was developed for semiconductors in which the minimum energy for direct transitions from the valence band to the conduction band is reached at points in $\mathbf{k}$ space where $\mathbf{v} = \partial E/\partial \mathbf{k} \neq 0$. In this case a system of exciton bands appears at the edge of interband absorption. Their frequencies are expressed conventionally through the curvatures of the electron and hole bands; the existence of nonzero band slope is manifested by the Doppler shift $\Delta\omega = \mathbf{K}\cdot\mathbf{v}$, where $\mathbf{K}$ is the photon quasi-momentum. Since $\mathbf{K}$ is finite this term leads to an angular dependence of frequencies that is different for excitons formed near different points of maximum band proximity.

E. F. Gross, B. P. Zakharchenya and **O. V. Konstantinov**: "The Effect of Magnetic Field Reversal on the Exciton Absorption Spectrum of CdS." Shifts and intensity changes of CdS absorption lines were observed when the magnetic field $\mathbf{H}$ was reversed. It follows from Onsager's principle that this can only occur in the presence of spatial dispersion and in the absence of an inversion center. In CdS-type crystals excitons can carry a dipole moment $\mathbf{d}$ oriented along the hexagonal axis. The interaction of this dipole moment with the electric field $\mathbf{E} = \frac{1}{c}\mathbf{v}\times\mathbf{H}$ in the center-of-mass system of an exciton moving with velocity $\mathbf{v}$, results in the energy term $\frac{-1}{c}(d\mathbf{v}\times\mathbf{H})$. This is absent in the case of impurity absorption and can serve to distinguish exciton from impurity absorption.

É. I. **Rashba** inquired about the relationship between this work and the work of Thomas and Hopfield.[5] Konstantinov replied that the experimental spectra observed in the two investigations contain differences, requiring different interpretations. I. B. Levinson inquired why the effect can be observed only for the n = 2 series term; Konstantinov suggested that for this line an optimum relationship is reached between several factors determining the effect.

A. A. Demidenko: "The Microtheory of Frenkel' excitons, with and without Retardation, in Cubic Crystals." In the HLH approximation the forms $E(\mathbf{k})$ of exciton zones in cubic crystals were determined neglecting long-range Coulomb forces. The dipole interaction was taken into account, as well as the overlapping of ψ functions of neighboring molecules. $E(\mathbf{k})$ was derived for small arbitrarily oriented $\mathbf{k}$ and for large $\mathbf{k}$ in the C_4, C_3, and C_2 directions. One longitudinal and two transverse exciton zones are obtained. $E(\mathbf{k})$ at the point $\mathbf{k} = 0$ is a nonanalytic function of k_x, k_y, and k_z. The Hamiltonian of the crystal plus the electromagnetic field is diagonalized. The dielectric constant $\epsilon(\omega, k)$ and the function $\omega(\mathbf{k})$ are found for an "optical exciton." The frequency of one optical-exciton branch for $\mathbf{k} \to 0$ agrees with the frequency of the longitudinal branch. As $\mathbf{k}$ increases, the frequency of the other branch approaches the dependence for a mechanical exciton.

V. S. Mashkevich: "Electromagnetic Waves in a Medium with a Continuous Energy Spectrum (Allowing for Spatial Dispersion)." The field strength E and crystal polarization are related by the integral equation $\mathbf{P}(\mathbf{r}) = \int K(\mathbf{r}, \mathbf{r}')\mathbf{E}(\mathbf{r}')d\mathbf{r}'$. Relations are obtained between the Hermitian and anti-Hermitian parts of the kernel $K(\mathbf{r}, \mathbf{r}')$, as generalizations of the Kronig-Kramers formulas. Using an explicit expression for K in the case of excitons at T = 0, the passage of an electromagnetic wave through a plate is considered. The coefficient of normal reflection is derived, taking the additional waves into

account. The results differ from those obtained by Pekar, since the theory does not require the vanishing of polarization at the boundary.

In the discussion I. M. **Lifshitz** and M. I. **Kaganov** expressed doubt about the possibility of dropping the boundary condition on the polarization **P**. This boundary condition appears to be contained implicitly in the derivation of the formula for $K(\mathbf{r}, \mathbf{r}')$. Pekar emphasized that the intrinsic functions of an excited crystal (exciton), which are used in calculating **P**, must satisfy boundary conditions that are equivalent to $\mathbf{P}_{\text{bound}} = 0$.

V. L. **Strizhevskii**: "An Investigation of Some Characteristics of Dispersion and Exciton Absorption of Light in Crystals." The dispersion and absorption of light by crystals are considered for allowed transitions to discrete and continuous states. In the first case the Dirac perturbation theory cannot be used, and spatial dispersion plays an important part, whereas it can be neglected in the second case. The van Hove method was used to consider dissipative processes, and the complex crystal polarizability was obtained at temperatures different from zero.

In the discussion V. M. **Agranovich** doubted that the theory can be applied to cases of large oscillator strengths, when retardation seriously distorts $E(k)$ for an exciton. V. I. **Perel'** criticized the statement that the Kronig-Kramers relations are not fulfilled, even when spatial dispersion is not taken into account.

V. T. **Cherepanov** and V. S. **Galishev**: "Anisotropy of Quadrupole Exciton Absorption in Cubic Crystals." Group theory was used to investigate the selection rules for optical transitions to an exciton state with O_h symmetry, but without using a specific exciton model. Quadrupole transitions are possible to states with Γ'_{25} and Γ_{12} symmetry. The experimental polarization dependence of absorption intensity in Cu_2O corresponds to the Γ'_{25} state. Line splitting is predicted for crystal compression in different directions.

In the discussion A. G. **Zhilich** pointed out that the theory does not consider magnetic dipole transitions to Γ'_{15} states, which are just as intense as quadrupole transitions. He mentioned his own calculations of bands in Cu_2O, according to which an exciton is formed out of electron and hole states lying close to the extrema of Γ_1 and Γ'_{25} bands.

E. F. **Gross**, A. G. **Zhilich**, B. N. **Zakharchenya**, and A. A. **Kaplyanskii**: "The Effect of Magnetic Fields and Crystal Deformation on the Exciton Ground State of Cu_2O." The behavior of the $n = 1$ line of the exciton yellow series in Cu_2O in a magnetic field and under uniaxial compression were investigated both theoretically and experimentally. Γ'_{25} symmetry was assigned to the corresponding exciton level. The splitting and polarization of components were determined for different cases. Good agreement was found between theory and experiment.

In the discussion S. A. **Moskalenko** remarked that he had reported partially similar theoretical results regarding pressure effects at the Thirteenth Conference on Spectroscopy.

S. A. **Moskalenko**: "On the Exciton Energy Spectrum in Undeformed Ionic Crystals." Possible Mott-Wannier exciton states are discussed, formed out of electron and hole states in Cu_2O and NaCl. The experimental results obtained by Gross and Kaplyanskii are easily accounted for by assuming that the upper valence band consists of 3d states of Cu^+. The splitting of exciton lines in external fields or in the presence of deformation is considered. The peaks of intrinsic absorption in alkali halide crystals are interpreted. The possibility of bi-excitons is discussed, as well as the properties of a degenerate slightly nonideal exciton gas. The possibility of a superfluid exciton gas is mentioned.

V. M. **Agranovich**: "On the Theory of Excitons in Molecular Crystals." A theory is proposed for the mixing of exciton states in molecular crystals as a result of intermolecular interaction; this differs from the Craig theory in that the contribution from a few nearest neighbors is calculated exactly. States involving the excitation of two molecules are also considered. For realistic values of the parameters the considered terms change the polarization ratio by a factor of the order 1.5.

I. G. **Zaslavskaya**: "Calculation of Excited Exciton States for Intermediate Coupling." The 2p state of a Mott exciton was considered, using the Buĭmistrov-Pekar variational method.[6] The energy levels are lower than those calculated by other methods and differ considerably from those calculated from the hydrogen-like formula.

S. V. **Vonsovskii**, P. S. **Zyryanov**, A. N. **Petrov**, and G. G. **Taluts**: "The Shapes of Exciton Absorption Lines in Electric and Magnetic Fields." The Toedzava theory for the shapes of exciton absorption bands is generalized to take account of electric fields. The field dependence of band energy and shape is determined. The form of large-radius exciton absorption bands in strong magnetic fields is determined, taking account of the quantization of electron orbits in the case of weak exciton-phonon coupling.

L. É. **Gurevich** and I. P. **Ipatova**: "On the Theory of Long-Wave Light Absorption by Crystals." This is an investigation of the infrared absorption mechanism involving photon-induced excitation of an electron-hole pair that is annihilated with the formation of one or two phonons. The two-phonon mechanism is more intense; its intensity increases steeply when the slopes of the two participating phonon branches are equal and opposite.

V. M. **Agranovich** and V. L. **Ginzburg**: "On X-Ray Scattering with Exciton Production in Crystals." Raman scattering of x rays accompanied by exciton production is considered. The scattering cross sec-

tion is only one order of magnitude smaller than the cross section for scattering on free electrons. We can therefore expect that an investigation of the way in which the change of x-ray wavelength depends on the scattering angle will lead to the dispersion law $E(k)$ for excitons.

L. N. Ovander: "Raman Scattering in Crystals." Raman scattering is regarded as the decay of a single light-exciton into two (Stokes scattering), and the transformation of two light-excitons into one (anti-Stokes scattering). A formula is derived for scattering intensity vs the incident light frequency and the wave vector direction of the scattered light-exciton. For small interactions the formula becomes identical with that obtained by perturbation theory.

In the discussion, replying to questions by **V. M. Agranovich** and **L. N. Demidenko, Ovander** added that the theory does not lead to divergence at the resonance point when interaction with radiation is taken into account.

É. I. Adirovich: "The Exciton as a Phase-Transformation Wave." It is suggested that in polymorphic materials an exciton localized at a phase interface can remove the activation barrier as a result of changing dynamic conditions. The lattice is rearranged and the phase interface is shifted; this in turn causes displacement of the exciton. The possibility of an exciton mechanism of polymerization is mentioned, and appropriate formulas are derived.

In the discussion **I. Lifshitz** stated that the idea of the paper is interesting, but that its mathematical formulation is unconvincing and redundant in its present form. He suggested that an exciton can induce a phase-transformation wave without removing the activation barrier, by imparting the necessary first impulse, after which a wave similar to a twinning wave will be propagated. On the other hand, in Adirovich's opinion it is improbable that this process can be applied to polymerization, since according to chemical data the evolved energy is removed practically instantaneously with the reactive degree of freedom, and kinetic energy cannot propagate the process.

Z. S. Kachlishvili: "Elastic Scattering of a Non-localized Exciton on Impurity Centers." The cross section for exciton scattering on interstitial ions or vacancies is found in the Born approximation. The field of a defect consists of the Coulomb field $\pm e/\epsilon r$ and the short-range field, differing for different ions. The Coulomb field plays the principal role for slow excitons. The temperatures are estimated below which impurity scattering predominates over lattice scattering. In the discussion **V. L. Bonch-Bruevich** noted that the Born approximation cannot be used for slow excitons. When the electron and hole have similar effective masses, scattering disappears in first approximation and the next approximation must be considered.

A. S. Selivanenko: "Calculation of the Scattering Cross Section for Free Excitons on Defects of a Molecular Crystal Lattice." The scattering cross section for Frenkel excitons on a foreign molecule was calculated in the HLH approximation using Green's functions. At $\sim 10^{17}/cm^3$ defect concentration the mean free path is comparable with that for lattice scattering at room temperature.

Many critical comments were made. It was pointed out, particularly, that one cannot legitimately neglect the difference between the excitation energies of the proper and foreign molecules.

A. A. Vorob'ev: "Intrinsic and Additional Absorption in Ionic Crystals and the Lattice Energy." A number of experimental regularities are presented concerning the intrinsic and impurity absorption bands in ionic crystals as functions of the lattice energy. With decreasing binding energy the bands are shifted toward longer wavelengths.

2. THE BAND STRUCTURE OF SEMICONDUCTORS

The papers under this heading were concerned with the group-theoretical analysis of band structure, quantitative calculations of bands in specific materials, liquid semiconductors, dislocation bands etc.

O. V. Kovalev: "On the Degeneracy of Electron Energy Levels in Crystals." The method of weighted representations[7] was used to construct matrices of single-valued and double-valued irreducible representations for all symmetry points of Brillouin zones, for all 230 space groups.

A number of persons expressed regret that the publication of this valuable reference material had not been arranged. Levinson stated that he had also used the procedure in reference 7 to construct representations of space groups.

T. I. Kucher: "Hole Bands in Alkali Chlorides." A review is given of hole band calculations for chlorides of Li, Na, K, and Rb using Hartree functions for Cl^-. The actual valence band maxima lie in 12 directions [110] within the Brillouin zone; the constant-energy surfaces near them are triaxial ellipsoids. The results obtained for widths and edges of the hole bands are compared with experiment and with Howland's calculations.

In the discussion **K. B. Tolpygo** emphasized that a many-electron treatment of hole bands is not qualitatively different from a single-electron treatment. The quantitative differences are associated with 1) deformation of the ψ function of the ion where a hole is located, 2) deformation of the neighborhood, and 3) change of the superposition integral due to the adiabatic succession of normal-ion states as the hole migrates. **N. N. Kristoffel'** and **P. N. Nikiforov** commented on the important change of ψ functions for atoms combined in a crystal, which should affect the quantitative results.

F. M. Gashimzade and **V. E. Khartsiev**: "The Energy Structure of Certain Semiconductors." Electron energies in the valence and conduction bands of Si, Ge, and GaAs are calculated for $\mathbf{k} = 0$ and $\mathbf{k} = \pi/a$, 0, 0 by the OPW method with orthogonality conditions replaced by an effective repulsive potential (following Antonchik) and with the ψ functions of the atom cores approximated by Slater functions. The results for Si and Ge differ relatively little from those obtained by other authors. It is concluded that crystal symmetry influences the general band picture more than the exact form of the potential does.

E. I. Cheglokov and **V. A. Chaldyshev**: "The Symmetry of Solutions of the Hartree-Fock Equations for Crystals." The symmetry properties of Hartree-Fock functions for crystals are discussed and compared with the properties of Bloch functions. It is stated that the relationship $E(\mathbf{k}) = E(-\mathbf{k})$ can be violated for hole bands.

In the discussion **Rashba** stated that violation of this relation should not be expected, since it is not associated with the use of Bloch waves and follows directly from time-reversal symmetry, which characterizes exact many-electron functions.

A. E. Glauberman, A. M. Muzychuk, M. A. Ruvinskii, and **I. V. Stasyuk**: "Problems of the Many-Electron Theory of Solid and Liquid Semiconductors." The earlier polar model of a crystal with open spin background is extended to include spin excitations (quasi-magnons). This furnishes considerable advantages for the description of band electrons and holes. The magnetic susceptibility is calculated. The procedure for considering light absorption[8] in atomic crystals is extended to the many-electron theory. The creation of a virtual electron-hole pair by a photon, and the production of excitons through pair annihilation are considered. A many-electron theory of impurity bands is developed, yielding a greater band width than results from direct interactions between impurity centers. A many-electron theory of liquids is developed. The Hamiltonian representing second quantization after averaging over the classical Gibbs function depends on statistical correlation functions. The characteristics of the spectrum of the system (effective masses, smearing of band "edges" etc.) depend on the binary distribution function and thereby on temperature.

In the discussion **Pekar** criticized the artificial averaging procedure, which does not follow logically from the formalism of the theory. Replying, **Glauberman** emphasized the complexity of the problem as requiring the given form of approximation; he had carried out a consistent program in a simpler problem of gas optics. **Agranovich** remarked that he has treated a molecular liquid similarly.

A. I. Gubanov: "On Different Theories of Amorphous Semiconductors." According to earlier work by the same author, for the model of an infinite liquid with slightly disturbed short-range order the energy spectrum retains a band structure with sharp band edges. Numerical calculations performed by other authors, on the contrary, indicate the smearing of band edges as disorder increases. In this paper the author concludes that the smearing of the edges is associated with the finite number G of atoms assumed in the aforementioned calculations, and that this effect should disappear as $G \to \infty$.

L. D. Dudkin: "On Chemical Bonds in Semiconductor Compounds of Transition Metals." The appearance of semiconductor properties is associated with the size of the parameter $\Delta = (a - d_m)/a$, where a is the separation of metal atoms and d_m is their diameter. With $\Delta > 0.145$ and saturation of the metal-nonmetal bonds, semiconductor properties should appear. Schemes are proposed for the bonds between atoms in different compounds of transition metals with Si, As and S, and the character of the conductivity of these compounds is accounted for.

A. D. Chevychelov: "Electron Energy Spectrum for a Polymer Chain Model." Using a simplified model for an electron in a polymer chain consisting of links at random angles, a cosine dispersion law is derived, with coefficients depending on the chain configuration.

In the discussion **É. L. Nagaev** and **É. I. Rashba** noted that the employed approximation is very crude, and that no reliable criterion of its applicability exists.

3. TRANSPORT PHENOMENA

The papers under this heading were concerned with the method of the deformation potential, with galvanomagnetic, thermomagnetic and photomagnetic effects in both weak and strong magnetic fields, and with the theory of hot electrons.

G. E. Pikus, G. L. Bir, and **É. S. Normantas**: "The Theory of the Deformation Potential and Carrier Scattering in Semiconductors with a Degenerate Band." The theory of the deformation potential is extended to semiconductors with a degenerate band. For the energy change in the band $E(\mathbf{k})$ with uniform crystal deformation the equation derived is $\mathrm{Det}\,|\hat{S}(\mathbf{k}) + \hat{D}(\epsilon) - E| = 0$, where $\hat{S}$ is the Shockley matrix, and $D_{ij} = \sum_{\alpha\beta} D^{ij}_{\alpha\beta}\epsilon_{\alpha\beta}$, and $\epsilon_{\alpha\beta}$ are components of the deformation tensor. For Si and Ge the matrix $\hat{D}$ is characterized by three constants. Electron scattering on acoustic phonons can be formulated by means of equations with effective masses for the smoothed functions, $F_j \| S(k) + D^A \| F = i\hbar(\partial F/\partial t)$. The matrix D^A coincides with $\hat{D}(\epsilon)$. For optical phonons D^A is replaced by D^0, which contains a single constant characterizing the effect of a relative displacement of two sublattices. The probabilities obtained for scattering within a band and between bands are complicated functions of $\mathbf{k}$ and $\mathbf{k}'$. The probabilities of scattering on acoustic phonons are obtained neglecting anisotropy. The kinetic equation is solved taking account of interband transitions.

Replying to a question by **V. A. Chuenkov, Bir** commented that the given treatment is more general than that of Overhauser and Ehrenreich, whose approximation is equivalent to the approximation with a single constant in the deformation potential.

E. P. Pokatilov: "The Interaction of Free Electrons with Ultrasound in Silicon and Germanium." The electroacoustic field is calculated for $\omega\tau > 1$, taking account of the anisotropy of effective masses, deformation potentials and elastic constants, as well as scattering on longitudinal and transverse acoustic phonons. Angle diagrams are obtained for the electroacoustic effect in Si and Ge. The field is obtained for $\omega\tau \ll 1$, assuming that the wavelength is considerably longer than the sample. In this case the effect is almost isotropic and is mass-independent; it can serve for the measurement of deformation potentials. The angle diagrams are sensitive to the locations of extrema and to the anisotropy of the mass tensor and deformation potential.

V. L. Gurevich and **Yu. A. Firsov:** "The Theory of Semiconductor Conductivity with Inelastic Scattering in a Magnetic Field." The transverse conductivity of a nondegenerate electron gas in a strong magnetic field H is investigated, with scattering on acoustic and optical phonons in both the classical region ($h\Omega \ll 2kT$) and quantum region ($h\Omega \gg 2kT$). (Ω is the Larmor frequency.) The results are compared with those obtained from the kinetic equation and from the theory in reference 9. In the classical region where $\hbar\omega_0 \gg kT$ (ω_0 being the optical phonon frequency), $\sigma(H)$ has a multistep character. When $\omega_0 > \Omega$ the conductivity oscillates, passing through a maximum when ω_0 is a multiple of Ω. Conduction involves both thermal electrons with energies $\sim kT$ and those scattered by an optical phonon, despite their small number, since these electrons have a proportionately shorter mean free time (the conductivity varies as $1/\tau\Omega^2$). A magnetic field region exists where $\tau\Omega \gg 1$ for thermal electrons and $\tau\Omega \ll 1$ for fast electrons. In the quantum region for $\omega_0 \gg \Omega$ far from the oscillation peaks, the conductivity varies as $1/H^2$.

I. Lifshitz emphasized the fundamental novelty of the idea of oscillating conductivity for a nondegenerate gas.

A. I. Ansel'm and **B. M. Askerov:** "Thermomagnetic Effects in Semimetals in Strong Magnetic Fields." Assuming square-law dispersion for $\Omega\tau \gg 1$ and an arbitrary relationship between $\hbar\Omega$ and kT, the longitudinal j_x and transverse j_y currents were calculated, depending on the temperature gradient $\nabla_x T$ ($H = H_z$). It is taken into consideration that the distribution function for $T = T(x)$ differs for different positions x_0 of the Landau orbit centers. x_0 changes as a result of scattering, i.e., electrons are displaced in the direction of ΔT. In the quantum case $\hbar\Omega \gg kT$ the Nernst coefficient is proportional to T^4/H and $T^{7/2}/H^2$ for a degenerate and nondegenerate electron gas, respectively.

In the discussion **G. M. Nedlin, O. V. Konstantinov** and others expressed doubts about the use of the zeroth approximation for scattering in calculating the Hall current j_y.

L. É. Gurevich and **G. M. Nedlin:** "The Contribution of Phonon Drag to Electronic Thermal Conduction." The technique of Konstantinov and Perel' was used to derive a system of kinetic equations for electrons and phonons in the quantum region $\hbar\Omega \gg kT$, and Onsager's principle was proved. A theory was developed for thermoelectric power in a quantizing magnetic field. The Herring case is considered in which electrons are carried along with long-wave phonons and the latter are slowed down on short-wave phonons; also the anti-Herring case, in which long-wave phonons are carried along with short-wave phonons, and phonons are slowed down at crystal defects and boundaries.

I. Ya. Korenblit: "Galvanomagnetic Effects in Bi_2Te_3 with Anisotropic Scattering." The kinetic equation is solved for the Bi_2Te_3 crystal in weak electric and magnetic fields. The calculation is based on the six-ellipsoid (six-valley) model of Drabble and Wolfe.[10] Expressions are obtained for the components of the conductivity tensor $\sigma(H)$ and relations are found between its coefficients, checking of which can supply information regarding the validity of the assumed band model and scattering anisotropy.

F. G. Baksht: "The Faraday Effect for Free Carriers in Bi_2Te_3 in Weak Magnetic Fields." In the relaxation-time tensor approximation with $\tau \sim E^{-1/2}$ as applied to the Drabble-Wolfe model, the kinetic equation is solved in a weak magnetic field. The admittance tensor is calculated for Bi_2Te_3, and formulas are obtained for calculating the Faraday effect.

In the discussion **M. I. Kaganov** remarked that he and F. G. Bass had already solved an analogous problem for arbitrary magnetic fields (published in the "Zapiski" of the Khar'kov State University).

G. I. Kharus and **I. M. Tsidil'kovskii:** "Anisotropy of Photomagnetic Effects in Cubic Crystals." The results obtained in this theoretical investigation account for the anisotropy observed in Ge by Kikoin and Bykhovskii.

N. P. Keklidze: "Some Electrophysical Properties of Germanium and Silicon at Low Temperatures." Formulas derived by Adirovich were applied to the separate determination of acceptor and donor concentrations in several samples of Ge and Si from the temperature dependence of the Hall constant R (or resistivity). The theoretical and experimental mobilities were compared. The dependences of R and magnetoresistance on T and H were studied.

V. B. Fiks: "Ion Drag by Electrons in Semiconductors." Electron scattering on impurity centers in an electric field produces a force acting on the impurity centers and their drag by electrons. The motion of neutral centers results entirely from drag by electrons; for charged centers the drag force is sub-

tracted from the direct action of the field on the center. In the case of mixed conduction the entrainment of centers by both electrons and holes must be taken into account. Investigation of the drift of neutral and charged centers can become an independent method of studying the mechanisms of impurity scattering and diffusion.

I. M. **Dykman** and P. M. **Tomchuk**: "Electrical Conductivity and Thermionic Emission in Semiconductors." The method of moments was used to solve the kinetic equation for the symmetric and antisymmetric parts (f_0 and f_1) of the electron distribution function in a strong electric field. The solution was obtained for square-law dispersion, taking into account interelectronic interactions (according to Landau) and scattering on phonons and impurities. For sufficiently high electron concentration but not too high energies, f_0 is Maxwellian with T_e exceeding the lattice temperature T_0. At high energies f_0 is Maxwellian with $T'_e = T_0$ but with a considerably larger coefficient of the exponential. The field dependence of the mobility μ and thermionic emission are derived. In the region of impurity scattering μ is approximately twice as large as that calculated from the distribution function of Fröhlich and Paranjape.

Bonch-Bruevich expressed the opinion that scattering on plasmons should also be taken into account, accompanied by a change of the electron interaction law. On the other hand, Dykman calculated that scattering on plasmons is unimportant for real parameters.

P. M. **Tomchuk**: "Variational Method of Determining Electrical Conductivity taking Account of the Coulomb Interaction between Carriers." The variational principle for f_1 is formulated. This is the basis for the method of moments used in the preceding paper.

Sh. M. Kogan and **V. B. Sandomirskii**: "On the Theory of the External Emission of Hot Electrons from Semiconductors." For the case in which the collision ionization energy V_i exceeds the electron affinity φ, the thermionic current density j emitted by a semiconductor is calculated as a function of the field and lattice temperature T_0, taking into account collisions with acoustic and optical phonons. In strong fields j increases as T_0 is reduced, and for germanium with a lower work function it can reach 10^2 amp/cm^2. For $V_i < \varphi$ the field has only a small effect on thermionic emission.

In the discussion **Dykman** expressed the opinion that the neglect of the term $\sim E^2$ in $f_0 \sim \exp[-(aE + bE^2)]$ (where E is the electron energy) is unjustified, and that the value of j is too high.

V. A. **Chuenkov**: "Electrical Conductivity of Germanium at Low Temperatures in Strong Electrical Fields." Solution of the kinetic equation gave the rate of collision ionization of impurity centers and the recombination rate as functions of the electric field strength at low temperatures. The current-voltage characteristic was obtained in the region of low-temperature electric breakdown associated with the intense collision ionization of shallow donors. The theory agrees with experiment.

V. P. **Shabanskii**: "Nonequilibrium Processes in Impurity Semiconductors." The kinetic equation is solved for band electrons taking account of the collision ionization of impurity centers. Formulas are obtained for the effective temperatures T_e and T'_e of the electron gas for small and large energies ($T_e > T'_e > T_0$) and for electron concentration as a function of field strength.

O. N. **Krokhin** and **Yu. M. Popov**: "Slowing-Down Time of Nonequilibrium Carriers in Semiconductors." From the kinetic equation with account of Fermi degeneracy it is shown that nonequilibrium carriers are slowed down in semiconductors in two stages, on optical and then on acoustic phonons. For Ge and Si the second stage is about 10^2 times longer than the first stage; the times for the second stage are 4.5×10^{-10} and 5×10^{-11} sec, respectively.

In the discussion **Rashba** noted that for concentrations large enough for degeneracy, collisions between electrons should play a large part.

Bonch-Bruevich and **Kaganov** emphasized the important role of Umklapp processes in semiconductors with many-valley band structure, because of the large momentum changes in these processes. The same applies equally to all work on the problem of hot electrons. **Z. S. Gribnikov** mentioned the current importance of studying electron gas heating in real semiconductors taking account of their inhomogeneity, and specifically, carrier diffusion in p-n junctions and the effect of the surface inversion layer.

4. RESONANCE AND OSCILLATORY EFFECTS

Several papers considered carrier behavior in a magnetic field within crystals with complex band structure. Theories were developed for quasi-classical quantization, resonance absorption of uhf waves and ultrasound by band carriers, oscillations of magnetic susceptibility, and paramagnetic resonance.

I. M. **Lifshitz**, V. M. **Nabutovskii**, and **A. A. Slutskin**: "On the Motion of Charged Quasi-Particles near Singularities of Constant-Energy Surfaces or Trajectories." Electron motion is considered near the dynamic singular points on both sides of which the intersections of a constant-energy surface by planes perpendicular to H have different connectivity. In a magnetic field varying slowly in time or space, as a simply-connected trajectory approaches a singular point an electron is scattered into one of the branches of a multiply-connected trajectory. The probabilities of scattering into different branches are determined by the geometry of the constant-energy surface ("scattering on a singularity"). In static or low-frequency

magnetic fields resonance absorption of uhf waves is possible by electrons with a steady period of revolution T ($dT/dt = 0$). The absorption is especially enhanced when at the same time $d^2T/dt^2 = 0$.

In reply to a question by **Bonch-Bruevich, Lifshitz** explained that "scattering on singularities" does not itself produce resistance, but that when other scattering mechanisms are present it affects conductivity through the distribution function.

M. Ya. Azbel': "A New Resonance Effect." When cyclotron resonance is measured in a metal, the complex pattern of field distribution through the depth of a sample contains a system of sharp spikes, which are replaced by regular oscillations at large distances. The spikes result from "piling up" of the field by resonating electrons. As the magnetic field is rotated, when an integral number of orbits fit within the thickness of the sample the surface impedance passes through an extremum. Observation of the effect requires an essentially nonquadratic dispersion law, a thin skin layer and large mean free path. Measurement of this effect should determine the Fermi surface.

M. Ya. Azbel': "Quasi-classical Quantization near Singular Classical Trajectories and Quantized Oscillations of Thermodynamic Quantities." A quasi-classical theory is developed for the motion of electrons near singular points of the Fermi surface. It is shown that oscillations of the thermodynamic quantities associated with details of the Fermi surface structure, such as sharp protrusions or depressions, can be observed experimentally and should be similar to oscillations associated with the presence of small electron groups.

É. I. Rashba, I. I. Boĭko, and V. I. Sheka: "Cyclotron and Combined Resonance and the Magnetic Susceptibility of Some Semiconductors." In some semiconductors the extremum of the electron bands can be reached on a circle in k space (the extremal loop). The existence of a region of negative effective mass and the infinite mass on the loop lead at low temperatures to singularities of the cyclotron resonance in a field perpendicular to the plane of the loop — to simultaneous absorption of the right- and left-hand waves, to the disappearance of distinct resonance in weak fields at low temperatures, to an oscillatory dependence of the cyclotron frequency on the magnetic field at extremely low temperatures etc. In strong fields that break the spin-orbit coupling the theory predicts a new resonance ("combined resonance" CR) at the frequency of spin resonance but excited by the electric field of the wave and 7 to 10 times more intense than paramagnetic resonance.[11] The angle dependence of CR is investigated. CR should also be observed in other semiconductors. A theory of CR is constructed for n-type InSb, where the spectrum of CR should be more complex. The investigation of the new resonance should permit measurement of a small spin-orbit divergence of the bands. The magnetic susceptibility of semiconductors with extremal loops is investigated.

V. L. Gurevich, V. G. Skobov, and Yu. A. Firsov: "Giant Oscillations of Sound Absorption." A highly degenerate electron gas is considered in a magnetic field, with $\zeta \gg \hbar\Omega \gg kT$ (where ζ is the chemical potential). Scattering on acoustic phonons is possible only with conservation of the oscillatory quantum number n. Therefore phonons can be absorbed only by electrons whose velocity component parallel to the magnetic field equals the velocity of sound (the sound wave propagates along the magnetic field). On the other hand, these electrons must have the energy $\hbar\Omega(n + \frac{1}{2}) + (p_z^2/2m) \approx \zeta$. This condition is fulfilled for several values of the magnetic field while $\hbar\Omega n < \zeta$. As a result there will be strong oscillations in the dependence of sound absorption on H.

M. F. Deĭgen and A. B. Roĭtsin: "Paramagnetic Resonance of Localized Electrons in Semiconductors for Arbitrary Values of the Static Magnetic Field." The hyperfine splitting of paramagnetic resonance lines is computed for an arbitrary static magnetic field and for zero field.[12] Selection rules and intensities are obtained for transitions induced by uhf waves. It is learned how absorption frequencies and intensities depend on crystal orientation with respect to constant and variable magnetic fields. Numerical results are given for F centers in KCl and for Ag atoms in NaCl.

V. Ya. Zevin: "On the Theory of Spin-Lattice Relaxation of Localized Electron Centers in Nonmetallic Crystals." The hyperfine interaction between electron spin and nuclear spins of nearest neighbors is considered as a cause of spin-lattice relaxation. The probability is found for electron spin reorientation for an F center in the LCAO model, and the changes of the coefficients of linear combination are determined in connection with displacements of nearest neighbors. Transition probabilities are calculated for one- and two-quantum transitions in interactions with acoustic phonons. The relaxation time τ varies both as T^2 and T^{-7}, for $T > \theta$ and $T \ll \theta$ (where θ is the Debye temperature). For an F center in KCl with $H \sim 3000$ oe, $\tau \sim 1$ min and $\sim 10^{-5}$ sec when $T = 4°K$ and $300°K$, respectively.

Replying to a question by **K. B. Tolpygo, Zevin** stated that the magnetic field associated with the current of vibrating nuclei should not appreciably affect relaxation, but that the effect of the spin-orbit interaction should be calculable.

Yu. V. Chkhartishvili: "Spin-Electron Resonance at an F Center of a KCl + NaCl Crystal." The ψ function of an F center in KCl was determined by the LCAO method for the case in which one of the six cations surrounding a chlorine vacancy is replaced by sodium. The coefficients of the linear combination are used to calculate the hyperfine splitting of the resonance line. The band consists of 208 lines, of which 16 are strongest. The separation of the respective extreme lines is 106 oersteds.

5. THEORY OF LOCAL CENTERS AND POLARONS

These papers treated the development of mathematical methods of calculation, the theory of impurity absorption and luminescence, and the theory of polarons.

K. K. Rebane and **O. I. Sil'd**: "The Method of Moments in the Theory of Electronic-Vibrational Transitions." The method of moments is formulated in a way that has technical advantages over that of M. Lax.[13] General formulas are obtained for the moments of the probability distributions of quantum-mechanical transitions. The results are applied to the theory of impurity absorption. The first three moments of the band for a local center are calculated in the Condon approximation taking account of frequency changes in phototransitions and of anharmonic terms.

V. M. Buĭmistrov: "The Variational Principle for Transition Probabilities." The accuracy of approximate calculations of quantum mechanical transition probabilities can be considerably improved by replacing the conventional functionals with others that agree with the conventional functionals for exact wave functions but, unlike the conventional ones, are stationary with respect to these functions. The construction of stationary functionals reduces to the solution of a derived differential equation. The method is applicable to a wide range of quantum mechanical problems.

S. V. Tyablikov and **V. A. Moskalenko**: "Application of Field Theoretical Methods to Many-Phonon Transitions." The probabilities of optical and nonradiative transitions in local centers are expressed in terms of temperature-time Green's functions, for which Wick's statistical theory leads to a simple system of differential equations. For example, this method easily takes into account small frequency changes in photo transitions. The proposed procedure is applicable to a wide range of problems.

Yu. E. Perlin, A. E. Marinchuk, and **V. A. Kovarskiĭ**: "Application of the Wigner-Weisskopf Perturbation Theory to Electron-Phonon Interactions in Crystals." Light scattering by an impurity-center electron is considered in the case of strong interaction with phonons. It is assumed that phonon relaxation does not take place between acts of light absorption and emission. In the absence of phonon dispersion the curve of the emission spectrum is broader than in Pekar's theory, with the same area and same position of the peak. Nonradiative transitions from virtual states cause the temperature dependence of the luminescent quantum yield.

A theory is presented for thermoluminescence associated with the previous tunneling of an electron from a shallow trap to an excited level of a deep trap (as in $F' \rightarrow 2F$ reactions). The spectral curve and temperature dependence of the reaction rate are obtained.

Impurity scattering of electrons through virtual single-phonon capture in shallow discrete levels is considered. This mechanism can predominate at low temperatures for large capture cross sections.

In the course of the discussion **K. K. Rebane** and **É. I. Rashba** remarked that in the absence of phonon relaxation the shape of the luminescence curve will depend on the frequency of the irradiation, which determines the degree of excitation of the vibrational system. In the opinion of Kristoffel', Tolpygo, and Kaganov, the phonon relaxation time resulting from anharmonic terms ($\sim 10^{-12} - 10^{-11}$ sec) is much shorter than the luminescence lifetime ($\sim 10^{-8}$ sec), and relaxation will always occur. Pekar pointed out that even in a pure harmonic approximation unstable crystal deformation near an excited impurity center inevitably disappears during a time of the order of a few vibrational periods of the lattice due to the spreading of the wave packet of optical vibrations.

A. M. Ratner and **G. E. Zil'berman**: "On the Theory of Luminescence in Crystals with Emitting Impurity Centers." The shape of the impurity absorption band is considered, assuming that in a center with small radius an electron interacts with a small number of vibrational coordinates, and taking account of the change of quasi-elastic interatomic forces in phototransitions. The theory accounts for the asymmetry of absorption bands and the departures from band symmetry in the cases of both absorption and luminescence.

Replying to questions by Pekar, Perlin, Rebane and others, **Ratner** insisted that the presented method is superior to the method of normal coordinates, since a small number of parameters is involved.

A. A. Tsertsvadze: "On the Absorption Mechanisms of F Centers and Excitons in Alkali-Halide Crystals." The required energy is calculated for the passage of an electron from a cation nearest to a halide vacancy to a cation in the next sphere. This energy is compared with the separation of the first and second peaks of fundamental absorption. The energy is also calculated for the passage of an electron from a halide ion to a neighbor of a vacancy; this is compared with the α band energy.

In the discussion **M. F. Deĭgen** and **K. B. Tolpygo** remarked that in order to obtain quantitative results in exciton theory one must consider electron transitions to s levels of neighboring halides, and also different states of a hole in the p shell of a halide.

A. G. Cheban: "The Theory of Thermal Ionization of F' Centers." The probability is calculated of thermal ionization of F' centers in NaCl and KCl taking account of the polaron effect, and the cross section for polaron capture by an F center.

D. I. Abakarov and **Yu. M. Seĭdov**: "The Theory of the Magnetic Susceptibility of a Polaron Gas." The magnetic susceptibility χ of a polaron gas in weak fields with weak electron-phonon coupling is calculated. A formula is derived for χ at low temperatures, differing from Landau's formula in that the electron mass

m is replaced by the polaron mass $M = m(1 + \alpha/6)$. At high temperatures the effective mass determined from the magnetic susceptibility depends on T.

V. L. Vinetskii: "The Ground State of a Bi-polaron." It is shown by means of the variational principle that in crystals with $n^2 \ll \epsilon$ (metal-ammonium solutions and ferroelectrics) the energy minimum of two polarons is reached at a finite distance between their centers. The energy is calculated that is due to exchange degeneracy and to the interaction of each electron with the polarization induced by the other electron.

In the discussion **Kaganov** remarked that exchange by acoustic phonons should contribute $\sim -1/R$ to the two-polaron energy. When this quantity exceeds the Coulomb repulsion $1/\epsilon R$, large-radius bound states are possible.

R. R. Dogonadze and **A. A. Chernenko:** "Electrical Conductivity of Semiconductors with Short Mean Free Path of Carriers." The electrical conductivity is calculated for semiconductors with small mobility of carriers that are small-radius polarons. This calculation generalizes the work of T. Holstein[14] and does not require the hypothesis that when an electron is localized at a lattice site only the nearest neighbors are displaced. The temperature dependence of the conductivity is considered.

Rashba noted that he had investigated a similar problem for excitons at low temperatures,[15] and pointed out the difficulties encountered in investigations of temperature dependences.

6. THE THEORY OF CRYSTAL LATTICES

A small number of papers treated the dynamics of crystal lattices, the relaxation of radiation defects, and crystal growth.

K. B. Tolpygo: "Long-Range Coulomb Forces in the Dynamics of Homopolar Diamond-Type Crystals." The role and magnitude of dipole-dipole interactions in nonpolar crystals and the coupling of nuclear displacements with atomic polarization are discussed. For long waves this coupling is weak and is responsible for birefringence, a few branches of the electromechanical vibrations near the frequency limit etc.[16] For short waves it causes long-range forces between uncharged atoms, in whose absence it would be impossible to account for the experimentally observed dispersion $\omega(\mathbf{k})$. The adiabatic approximation of crystalline potential energy is derived, improving earlier results[17] and substantiating the interaction proposed by W. Cochran.[18] The large polarization effects in Si and Ge are noted. Also given are estimates of parameters and a calculation of natural frequencies by T. I. Kucher and Z. A. Demidenko.

V. S. Oskot-skii and **A. L. Efros:** "On the Theory of Crystal Lattices with Noncentral Interatomic Interaction." A study is made of the conditions imposed on dynamic matrices of crystals by the requirement of no initial stresses and invariant energy density with respect to crystal rotation. The most general interaction is proposed in harmonic approximation, depending on the relative displacements of each triplet of atoms. Expressions for the elastic constants are obtained by the static deformation method. In the absence of initial stresses these constants agree with those obtained by the long-wave method.

B. Ya. Yurkov: "On the Theory of Annealing of Radiation Defects." Waite's theory of the annealing of radiation defects was extended to take account of the recombination of genetically unrelated vacancies and interstitial atoms. The solution correctly describes the process during long annealing times, and for Si leads to a ~ 20 Å capture radius.

M. Ya. Dashevskii and **M. S. Mirgalovskaya:** "On the Growth and Structure of $A^{III}Sb$ Single Crystals." A crystal faceted with $\{111\}$ planes can have surfaces at which A atoms emerge (type A) and surfaces at which Sb atoms emerge (type B). These surfaces have essentially different properties, and single crystals of InSb do not grow at equal rates in the directions (111), $(\bar{1}\bar{1}1)$, $(1\bar{1}\bar{1})$, $(\bar{1}1\bar{1})$ and the reverse directions. $A^{III}Sb$ crystals can depart considerably from the stoichiometric form. A model of type-A surfaces is proposed, in which In atoms do not possess a tetrahedral electronic configuration.

7. THE PHENOMENOLOGICAL THEORY OF SEMICONDUCTORS

This section combines papers on the phenomenological theory of photocarrier recombination, surface effects, and the magnetic reluctance of finite samples.

I. A. Mirtskhulava: "The Investigation of Traps in Semiconductors by Means of Prolonged Optical Excitation." Kinetic equations are solved for the number of electrons in the conduction band and in local levels immediately after the start and termination of exposure to light. For equal electron trapping cross sections of two kinds of local centers the nonlinear equations are solved exactly; for the general case the equations are solved approximately. The parameters of the local centers are determined by comparing the experimental and theoretical rise and decay curves of photocurrent.

É. I. Adirovich: "The Kinetics of Impurity Photoconduction and a New Way of Determining the Cross Sections of Local Centers." The kinetics of photoconduction in a semiconductor is investigated for the case in which carriers of only one sign are formed. In so far as the effect is not complicated by drift, surface and stepwise recombination, or the freeing of carriers, and the formulas are relatively simple, it is proposed that this effect be used to measure the recombination cross sections of different centers from the frequency dependence of the photocurrent.

Yu. V. Gulyaev: "The Statistics of Electrons and Holes in Semiconductors with Dislocations." Qualitative concepts regarding the energy spectrum of dislocation levels are used to determine the degree to which dislocations are populated with electrons, as a function of temperature and the position of the Fermi level. By extending the Shockley-Read recombination statistics to dislocation levels a formula is derived for the lifetime of minority carriers.

V. M. Fridkin: "On the Phenomenological Theory of the Photoelectret State of Crystals." A photoelectret state arises in a crystal that is acted on simultaneously by light and an electric field. The formation of the photoelectret state is described by a scheme containing electron trapping levels. A criterion for the fulfillment of the reciprocity law is discussed.

G. M. Guro: "Energy Structure of the Space Charge Surface Layer of Semiconductors." The potential created by the surface layer of space charge forms a potential well for electrons. When the dimensions of this well are smaller than the de Broglie wavelength and the electron mean free path, quantum effects must be considered. In this case the spectrum consists of a system of surface bands. The influence of the given effect on surface conduction is considered.

Yu. I. Gorkun: "The Influence of Electrodes on Reluctance." The potential distribution in a rectangular sample within a weak magnetic field is determined, taking into account finite dimensions and the short-circuiting effect of electrodes. Geometric criteria are indicated which must be observed for the correct measurement of reluctance.

Yu. A. Vdovin, B. M. Grafov, V. A. Myamlin, and **V. G. Levich:** "Properties of an Electrolyte-Semiconductor Interface." A theory is constructed to describe the passage of current through an electrolyte-semiconductor contact (for both ambipolar and unipolar conduction). Processes in the semiconductor are described by the equations of diffusion theory, and at the interface by a semiempirical formula of the theory of retarded discharge. Characteristics are obtained revealing a rectification effect. The dissolution rate of a semiconductor as current flows is calculated, and the theory is applied to Ge and Si. Surface conductivity of the electrolyte-semiconductor contact is considered.

8. THE THEORY OF SEMICONDUCTOR DEVICES

V. M. Val'd-Perlov, A. V. Krasilov, M. E. Lisogorskii, and **V. L. Aronov:** "Parametric Diodes and Calculation of the Parameters." The relationship between the characteristics of parametric amplifiers and the parameters of semiconductor diodes is investigated in order to determine the optimum values of the latter. Different diode types are considered (with different geometry and impurity distribution in the base), and also different operating modes (harmonically varying voltages or currents).

D. A. Aronov and **P. S. Karageorgii-Alkalaev:** "On One Possible Mechanism of the Growth of Reverse Current with Voltage in a Semiconductor Diode." A diffusion theory is constructed for the passage of reverse current through a semiconductor diode. The theory is valid for any distance w between the p-n junction and one of the metal electrodes, while the distance to the second electrode is assumed to be quite large. Carrier generation in space charge at the p-n junction and at the metal contact is considered. In the limit of small w the theoretical formulas for a chemical barrier layer are derived;[19] for large w the theoretical formulas for thick diodes are derived.[20]

M. I. Markovich and **N. M. Roĭzin:** "The Effect of Base Geometry on Transistor Transfer Characteristics." During operation at saturation minority carriers are accumulated in the passive region of the base. Their lifetime considerably exceeds the lifetime in the active part of the base, since they can migrate only by diffusion. The presence of a large number of unrecombined minority carriers leads to the self-triggering of transistors in trigger circuits. This effect can be used to measure lifetime in the passive part of the base.

A. L. Zakharov: "A Theoretical Investigation of Voltage-Current Characteristics of Injection in Barrier Layers." A simplified theory is developed for spacistors with point and linear emitters. Formulas are obtained for the slope of the characteristic and for the amplification factor.

Yu. S. Ryabinkin: "The Electric Field in a Semiconductor between Junctions." The field in the quasi-neutral part of a triode base is investigated approximately, for plane geometry, neglecting carrier recombination. The effect of space charge is evaluated.

Yu. S. Ryabinkin: "The Influence of Carrier Diffusion on the Transfer Coefficient of a Field-Effect p-i-n Transistor." A theoretical study is made of the influence of carrier diffusion on transistor frequency characteristics for a strong field E in the base, in which electrons drift at the limit speed. The distribution function of V. A. Chuenkov is used to calculate the diffusion coefficient $D \sim E^{-1/3}$. Carrier diffusion establishes the frequency limit of amplification.

In the discussion **Z. S. Gribnikov** and **V. B. Sandomirskii** commented that the formulas of the theory of hot electrons for homogeneous samples cannot be applied directly to inhomogeneous systems with gradients of concentration and electron temperature.

It should be noted that the papers on the theory of devices treat frequency problems, do not discuss new principles of the operation of semiconductor devices, and are insufficiently linked to the study of physical processes in semiconductors. It is unfortunate that the conference was attended by almost no leading experimental physicists who are semiconductor specialists.

In his concluding address **S. I. Pekar** mentioned the progress achieved in the electron kinetics of conduction bands, magnetic and resonance effects, and the theory of excitons, local centers and polarons. Insufficient work is being done on the calculation of energy bands, the many-electron theory of crystals, and the substantiation of band schemes. The problem of low-mobility carriers has not been worked out. There is inadequate liaison between theoreticians and experimenters, as is evident from the small number of experimenters present at the conference and from the very small number of papers on the theory of semiconductor devices.

In the name of all present Pekar expressed deep appreciation to the Tbilisi group of the organizing committee, headed by the late A. I. Gachechiladze, for their splendid work in preparing and organizing the conference.

The conference adopted a resolution commenting on the strong centralization of work on semiconductor theory in Moscow, Leningrad, and Kiev, and on the need for expanding work in the capitals of the various national republics and other cities of the Soviet Union. It is especially important to develop investigations of the complex band structure of semiconductors, resonance effects, carrier kinetics (including low mobilities, hot electrons, recombination, and nonradiative transitions), and the physics of imperfect crystals. New mathematical methods must be developed, particularly by adaptation from field theory, and computer methods must be introduced widely.

The desire was expressed to hold the next conference at Kishinev in 1962.

É. I. Rashba and K. B. Tolpygo

[1] S. I. Pekar, JETP **33**, 1022 (1957), Soviet Phys. JETP **6**, 785 (1958).

[2] E. F. Gross and A. A. Kaplyanskii, Физика твердого тела (Solid State Physics) **2**, 379 (1960), Soviet Phys.-Solid State **2**, 353 (1960).

[3] I. S. Gorban' and V. B. Timofeev, Report at Thirteenth All-Union Conference on Spectroscopy, Leningrad, July 1960.

[4] M. S. Brodin and S. I. Pekar, JETP **38**, 74, 1910 (1960), Soviet Phys. JETP **11**, 55, 1373 (1960).

[5] D. G. Thomas and J. J. Hopfield, Phys. Rev. Letters **4**, 357 (1960).

[6] V. M. Buĭmistrov and S. I. Pekar, JETP **32**, 1193 (1957), Soviet Phys. JETP **5**, 970 (1957); V. M. Buĭmistrov, Ukr. Phys. J. **3**, Suppl. I, 21 (1958).

[7] G. Ya. Lyubarskii and O. V. Kovalev, J. Tech. Phys. (U.S.S.R.) **28**, 1151 (1958), Soviet Phys.-Tech. Phys. **3**, 1071 (1958).

[8] L. É. Gurevich and Z. I. Uritskii, op. cit. ref. 2, **1**, 1298 (1959), transl. p. 1188.

[9] E. N. Adams and T. D. Holstein, J. Phys. Chem. Solids **10**, 254 (1959).

[10] J. R. Drabble and R. Wolfe, Proc. Phys. Soc. (London) **B69**, 1101 (1959).

[11] É. I. Rashba, op. cit. ref. 8, **2**, 1224 (1960), transl. p. 1109.

[12] M. F. Deĭgen and A. B. Roĭtsin, JETP **36**, 176 (1959), Soviet Phys. JETP **9**, 120 (1959).

[13] M. Lax, J. Chem. Phys. **20**, 1752 (1952).

[14] T. Holstein, Ann. Phys. **8**, 325, 343 (1959).

[15] É. I. Rashba, Izv. Akad. Nauk SSSR, Ser. Fiz. **21**, 37 (1957), Columbia Tech. Transl. p. 33; Оптика и спектроскопия (Optics and Spectroscopy) **3**, 568 (1957).

[16] V. S. Mashkevich and K. B. Tolpygo, Doklady Akad. Nauk SSSR **111**, 575 (1956), Soviet Phys.-Doklady **1**, 690 (1957).

[17] V. S. Mashkevich and K. B. Tolpygo, JETP **32**, 520 (1957), Soviet Phys. JETP **5**, 435 (1957).

[18] W. Cochran, Proc. Roy. Soc. (London) **A253**, 260 (1959).

[19] A. I. Gubanov, Теория выпрямляющего действия полупроводников (Theory of Semiconductor Rectification), Gostekhizdat, Moscow, 1956.

[20] É. I. Rashba and K. B. Tolpygo, J. Tech. Phys. (U.S.S.R.) **25**, 1335 (1955).

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