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Meetings and Conferences

SIXTH ALL-UNION SYMPOSIUM ON SEMICONDUCTOR THEORY

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THE Sixth All-union Symposium on the Theory of Semiconductors, sponsored by the Scientific Council on the Physics and Chemistry of Semiconductors of the Academy of Sciences of the U.S.S.R. jointly with the Academy of Sciences of the Moldavian S.S.R. and the University of Kishinev, took place from October 26 to 31, 1964 in Kishinev. There were 284 participants from 32 towns of the Soviet Union, with 128 papers presented. The meeting used the rapporteur system. There were 11 talks by rapporteurs which summarized the papers presented to the Conference and reviewed the state of the corresponding problems. In addition there were eight sectional meetings during the afternoons, in which 42 of the papers submitted to the Conference were read.

1. PLASMA PHENOMENA IN SEMICONDUCTORS

The review paper was given by **L. É. Gurevich** (A. F. Ioffe Physico-technical Institute, Leningrad). He noted that the study of plasma phenomena in solids follows at present three basic lines:

1. The study of the spectra of semiconductors in equilibrium.

2. The study of non-linear phenomena associated with the propagation of electromagnetic waves in the plasma of semiconductors.

3. The study of non-equilibrium aspects of the electromagnetic spectrum.

The papers submitted to the conference on the second subject included the paper by **F. G. Bass**, "The Non-linear Propagation of Electromagnetic Waves in the Electron-hole Plasma in Semiconductors," and that by **F. G. Bass** and **S. I. Khankina**, "On the Non-linear Theory of Electromagnetic Wave Propagation in Semiconductors," (Inst. of Radio and Electronics, Ukrainian Academy). The first paper treats the effects of the temperature rise of the current carriers on the propagation of electromagnetic waves. The kinetic equation is solved by iteration under the assumption that $\omega\tau_\epsilon \gg 1$, where ω is the frequency of the electromagnetic wave and τ_ϵ the energy relaxation time of the electrons, and this leads to corrections to the reflection, refraction, and damping coefficients. The paper also considers the effects of a constant magnetic field and in this connection takes into account the effect of the temperature rise of the carriers on the cyclotron and plasma-magnetic resonances. At resonance the electromagnetic wave is strongly absorbed and decreases exponentially. The second paper generalizes the results obtained in the first to the case of two types of current carriers.

Amongst the papers on the third subject one may distinguish two kinds:

1. Papers dealing with models showing a falling voltage-current characteristic i.e., having $\partial I/\partial E < 0$.

2. Papers dealing with secondary branches of the electromagnetic spectrum in the presence of an electric field and a temperature gradient and with or without external magnetic field. These branches are called galvanomagnetic waves (GMW) or thermomagnetic (TMW) waves; in the simplest cases they can be either purely longitudinal (no current oscillations but only oscillations of the field intensity E and the carrier concentration n) or purely transverse (oscillations of E or H and of the current I).

The paper of **V. L. Bonch-Bruevich** and **S. G. Kalashnikov**, "On Recombination Instability in Semiconductors" (Institute of Radio Engineering and Electronics of the U.S.S.R. Academy of Sciences) studies conditions in which the differential conductivity of the specimen becomes negative because of the variation of the trapping coefficient with carrier energy. It is found that in a system with two types of impurity one may under certain conditions find recombination instabilities and strongly anharmonic oscillations.

The second type includes the paper by **O. V. Konstantinov** and **V. I. Perel'** (A. F. Ioffe Physico-technical Institute), "Recombination Waves in Semiconductors," in which it is shown that a current in a semiconductor with widely different trapping times for electrons and holes can cause the propagation of recombination waves. At sufficiently high carrier concentrations and strong electric fields these waves can become self-excited. An expression is derived for the critical field which is a function of the lifetimes of electrons and holes and of their concentration.

Longitudinal GMW may change from conditions of weak damping to a condition of growth if the crystal has a gradient of any one of the parameters which affect the electric current. This can be the gradient of the carrier concentration or of their mobility or a non-uniformity of the external fields. This behavior is called a gradient instability. This type of instability will develop if more particles enter than leave a volume element in which there is a fluctuation.

The paper by **L. É. Gurevich, B. L. Gel'mont** and **I. V. Ioffe,** "Thermomagnetic and Galvanomagnetic Waves in Semiconductors," (A. F. Ioffe Physico-technical Institute) studies such GMW and TMW in semiconductors and metals. The paper considers various methods of setting up gradients of the parameters: light absorption, which creates on the surface of the crystal pairs of current carriers; ionization by collision, temperature gradients, non-uniform distributions of impurities etc. The basic equations of the problem are the continuity equation and the phenomenological equation for the current, which are linearized and solved by the WKB method, and also the Maxwell equations in the case of TMW. This leads to a determination of the critical values of the field intensities for which the instability sets in. It is shown that: (1) If the direction of the gradient of the conductivity and the electric field do not coincide, the critical value of the field depends on the state of the surface; (2) if the instability arises from the gradient of a certain parameter, there may be a "quenching" of the instability through the effect of another factor which is capable of producing a gradient of the same parameter in the opposite direction; (3) in intrinsic isotropic semiconductors, as opposed to impurity semiconductors, no instability occurs in the presence of a concentration gradient but without magnetic field; (4) if the gradient of the carrier concentration arises from an inclination between the electric and magnetic fields no instability appears if the angle between **E** and **H** exceeds a certain critical angle of the order of 10°; (5) if a radial gradient of carrier concentration is produced in a cylindrical specimen (e.g., by collision ionization) there will be a growing helical wave; (6) if one applies a temperature gradient instead of an external electric field, then there are unstable transverse TMW in the presence of a magnetic field. The paper gives criteria for the instability of TMW and describes a possible experiment with which they could be detected.

A number of papers dealt with effects connected with the heating of electrons in semiconductors. For example, **I. B. Levinson** (Institute of Physics and Mathematics of the Lithuanian Academy of Sciences) showed in his paper, "Relaxation Times Dependent on Heating and the 'Runaway' Effect of Hot Electrons in Semiconductors," that if the product of the momentum relaxation time τ_p and the energy relaxation time τ_ϵ increases at least proportionally with the energy ϵ of the electrons then above a certain field intensity one should observe an unlimited rise of the electron energy ("runaway" electrons). The mechanism limiting this "runaway" effect is the scattering by optical phonons when $\epsilon \gtrsim \hbar\omega_0$. According to the author this effect occurs in n-InSb at low temperatures when $\tau_p \sim \epsilon^{1/2}$ (impurity scattering) and $\tau_\epsilon \sim \epsilon^{1/2}$ (scattering by the piezoacoustical potential).

2. QUANTUM THEORY OF TRANSPORT PHENOMENA

A. L. Éfros (A. F. Ioffe Physico-technical Institute) spoke as rapporteur on "Quantum Theory of Transport Phenomena" and pointed out the unsatisfactory state of the general theory of quantum kinetics when applied to problems in which one cannot single out a perturbation in the Hamiltonian, and therefore in such problems cannot use a general formula of the Kubo type for calculating the electric conductivity. However, in spite of the lack of a general theory for problems of this type several particular cases have been solved satisfactorily. These include the calculation of the off-diagonal components β_{xy} and γ_{xy} in the presence of a strong magnetic field. The phenomenological transport equations are of the form

$$\left.\begin{aligned} \mathbf{j} &= \sigma\left[\mathbf{E} - \nabla\frac{\mu}{e}\right] - \beta\nabla T, \\ \mathbf{w} - u\mathbf{j} &= \gamma\left(\mathbf{E} - \nabla\frac{\mu}{e}\right) - \varkappa\nabla T, \end{aligned}\right\} \tag{1}$$

where the coefficients β and γ are connected by the well-known Onsager relation

$$\gamma_{ik}(H) = \beta_{ki}(-H)\,T. \tag{2}$$

A. I. Ansel'm and B. M. Askerov[1] took the temperature and the chemical potential as functions, not of the coordinate x, but of the coordinate of the center of the Larmor circle $x_0 = (c\hbar/eH)k_y$. They expanded the equilibrium distribution function in powers of $(x_0 - x)$ and introduced the temperature gradient, and thus obtained an expression for β_{xy}. However, this procedure does not satisfy the Onsager relation (2) or the Einstein relation.

Yu. N. Obraztsov[2] showed that the difficulty mentioned above disappears if one takes into account the corrections arising from the magnetism of the conduction electrons. Since the magnetic moment of the conduction electrons vanishes in the classical region because the volume moment cancels the moment of the surface currents, the calculation of these corrections is a pure quantum effect and an effect of the finite size of the crystal. The paper by Yu. N. Obraztsov has another important aspect: he shows that the current density entering in Eq. (1) is the macroscopic current density and is uniquely determined by the continuity equation and by the requirement that it should vanish in thermodynamic equilibrium. This leads to

$$\mathbf{j} = \mathbf{j}_M - c\,\mathrm{curl}\,\mathbf{M}, \tag{3}$$

where $\mathbf{j}$ is the macroscopic current density, $\mathbf{j}_M$ the average over a physically small volume of the density of microscopic currents defined uniquely by the relation

$$\delta\dot{\mathbf{H}} = -\frac{1}{c}\int \mathbf{j}_M \delta A\, dV, \tag{4}$$

and M the magnetization. A similar correction can

also be applied to the energy flux. This, however, cannot be obtained without difficulty from general thermodynamic considerations. Yu. N. Obraztsov obtained for the thermoelectric e.m.f. the formula

$$\alpha = -\frac{S}{e}, \qquad (5)$$

where S is the entropy per particle. In the derivation of this formula he used a definite form of the electron spectrum (a quadratic dispersion law) and so far no thermodynamic derivation of this formula has been given. There is therefore some interest in obtaining expressions for the non-dissipative part α for other forms of the spectrum. In the paper by **A. I. Ansel'm, Yu. N. Obraztsov** and **R. G. Tarkhanyan** (Semiconductor Institute of the U.S.S.R. Academy of Sciences), "Influence of a Non-Parabolic Spectrum on the Thermoelectric e.m.f. in Semiconductors in a Magnetic Field in the Quantum Region," the validity of Eq. (5) is proved for a non-parabolic dispersion law in semiconductors of the type of InSb. This work takes into account terms up to the order $\left(\mathbf{p}-\frac{\mathrm{e}}{\mathrm{c}}\mathbf{A}\right)^4$, as well as the electron spin. The inclusion of spin is necessary in this case since these semiconductors have large g factors. A paper by **Yu. N. Obraztsov** (Semiconductor Institute of the U.S.S.R. Academy of Sciences), "Thermoelectric e.m.f. in a Quantizing Magnetic Field," obtained Eq. (5) by means of a method similar to that used by Teller in the calculation of the diamagnetism of conduction electrons. The paper of **G. I. Guseva** (Metal Physics Institute of the U.S.S.R. Academy of Sciences), "Thermoelectric e.m.f. in n-Type Germanium in a Quantizing Magnetic Field," gives a calculation of the thermoelectric e.m.f. for a semiconductor with several minima in its spectrum and particularly for n-Ge, and shows the validity of Eq. (5) also for this case. It is shown that, depending on the orientation of the magnetic field in relation to the crystallographic axes, the minima of the conduction bands belonging to different equivalent points of k space are shifted by different amounts and this results in a strongly anisotropic thermoelectric effect. Yu. N. Obraztsov[3] showed that

$$\left(\frac{\partial M}{\partial T}\right)_{n,H} = ne\left(\frac{\partial \alpha}{\partial H}\right)_{n,T},$$

where M is the magnetic moment and n the carrier concentration. In degenerate superconductors the thermoelectric e.m.f. must therefore show de Haas–van Alphen oscillations, as was also shown by G. I. Guseva for n-Ge. Papers in which diagonal components such as β_{xx} were calculated include the work of **P. S. Zyryanov** (Metal Physics Institute of the U.S.S.R. Academy of Sciences), "On the Quantum Theory of Transport Phenomena in Semiconductors and Metals in a Magnetic Field." The method of calculation was similar to that introduced by A. I. Ansel'm and B. M. Askerov[1], who calculated in their paper not only β_{yx} but also β_{xx}: one considers the collision integral in which the chemical potential and the temperature are taken as functions of x_0, the coordinate of the center of the Larmor circle, and expands in powers of $(x_0 - x)$ in a linear approximation. This led to a peculiar form of the continuity equations for current and energy flux:

$$\frac{\partial n(x_0)}{\partial t} = -\frac{\partial}{\partial x_0} j(x_0) \text{ and } \frac{\partial \varepsilon(x_0)}{\partial t} = -\frac{\partial}{\partial x_0} w(x_0).$$

This leads to expressions for the coefficients β_{xx}, γ_{xx} and κ in Eq. (1), which satisfy the Einstein and Onsager relations when the corrections suggested by Yu. N. Obraztsov are allowed for. In addition the paper gives an expression for κ_{xy} which had not been obtained by Yu. N. Obraztsov.

In 1961 V. L. Gurevich and Yu. A. Firsov predicted a new effect of quantum oscillations in the transverse electric conductivity: a phonon-magnetic resonance due to the scattering of electrons by optical phonons in a strong magnetic field. Such oscillations differ from the Shubnikov–de Haas oscillations by being present for any kind of statistics and by having a different period $\Delta H^{-1} = e/mc\omega_0$ where ω_0 is the limiting frequency for optical phonons. The paper of **V. L. Gurevich** and **Yu. A. Firsov** (Semiconductor Institute of the U.S.S.R. Academy of Sciences), "Phonon-magnetic Resonance Oscillations in the Longitudinal Resistance of Semiconductors," develops the theory of this effect for the longitudinal magnetoresistance. It is shown that the maxima in the longitudinal and transverse resistance coincide, provided the scattering by optical phonons dominates. When the scattering by acoustic phonons is dominant a maximum in the oscillating part of the transverse magnetoresistance corresponds to a minimum of the longitudinal resistance. These conclusions agree with the experimental results of Shalyt, Parfen'ev, and Muzhdaba[17]. The paper by **S. T. Pavlov** and **Yu. A. Firsov** (Semiconductor Institute of the U.S.S.R. Academy of Sciences), "Phonon-Magnetic Oscillations in the Longitudinal Thermoelectric e.m.f. in Semiconductors," develops a similar theory for the longitudinal case. The paper by **V. P. Kalashnikov** and **G. G. Taluts** (Metal Physics Institute of the U.S.S.R. Academy of Sciences), "Non-linear Galvanomagnetic Phenomena in Semiconductors in Conditions of Strong Phonon Drift," deals with non-linear galvanomagnetic effects. Assume that there is a strong phonon drift caused by the electrons. Since in a strong magnetic field the transverse component of the conductivity tensor is proportional to the scattering, the drift effect will make it small. With increasing electric field the electron drift velocity cE/H increases. When it reaches the velocity of sound the phonons fall behind and the resistance increases sharply, and with it the transverse component of the conductivity. At the same time the voltage-current characteristic has a break which is the sharper the stronger the phonon drift.

3. BAND THEORY OF SEMICONDUCTORS

The rapporteur's talk was given by **K. B. Tolpygo** (Semiconductor Institute of the Ukrainian Academy of Sciences). In the study of the band structure of semiconductors there are two possible approaches: one is group theoretical and investigates the general regularities of the spectrum, and the other a quantitative calculation of the dispersion law for electrons in the various bands. In the first case the nature of the variation of the electron energy with wave vector in the neighborhood of certain characteristic points of the Brillouin zone or along certain symmetrical directions is determined from general symmetry considerations. The electron energy is then expressed as a power series in the displacement of the wave vector from the particular point of symmetry. Usually one includes only the quadratic terms. The expansion coefficients, whose number is reduced by the symmetry, are parameters of the theory and can be determined by comparison between experiment and theory on the various effects which are sensitive to the dispersion law (such as the cyclotron resonance). The advantage of this approach is its great generality and rigor. It does not, however, lead to definite quantitative results. In addition, the group-theoretical approach is limited to such energy values for which the one-particle excitations can be regarded as stationary. If one wants to determine which of the dispersion laws suggested by the general theory exists in reality one has to add further arguments taken from the analysis of experimental data. The first four papers reviewed by the rapporteur belonged to the group theoretical approach.

The paper by **N. V. Kudryavtseva** and **V. E. Stepanov** (Siberian Physico-technical Institute), "Dispersion Laws for Crystals with Cubic and Hexagonal Symmetry," takes into account both the space groups and the existence of rotational symmetry. The results are given in the form of tables of dispersion laws to second order near all typical points of the Brillouin zone for all space groups of crystals with cubic or hexagonal symmetry.

The paper of **G. F. Karavaev** (Siberian Physico-technical Institute of Physics), "New Method for Calculating Selection Rules for Matrix Elements in the Theory of Crystals," presents methods for determining the selection rules for indirect transitions allowing for all space-time symmetries of the crystal. The formulae show a very substantial simplification.

In another paper, "Structure of the Energy Spectrum of Compounds of the Type Me_2Z_3 of Rare Earths with Sulfur, Selenium, and Tellurium," **G. F. Karavaev** considers a structure of the type Th_3P_4 in which all phosphorus sites are occupied, but only eight of the nine thorium sites are filled. The empty sites are distributed at random over the lattice. It is assumed that on the average the Me_2Z_3 preserves the full symmetry of the Th_3P_4 lattice and this leads to conclusions about the energy spectrum. Various dispersion laws are considered and an effective-mass Hamiltonian is constructed for various possible positions of the band limit.

The papers next discussed by the rapporteur concerned the quantitative theory of electron dispersion in certain crystals which gave numerical results. Up to the present a few particularly efficient methods for such calculations have become known; they can be divided into two main groups: the self-consistent field method and the method of valence bonds. In the first case the problem reduces to the solution of the Schrödinger equation for one electron in a certain self-consistent potential field. For the conduction electrons this potential consists of the potential due to the atomic cores and that due to the valence electrons. According to Bloch's theorem the wave function can be written as a modulated plane wave $\Psi_{nk} = e^{ik\cdot r}u_{nk}(r)$. For the determination of $u_{nk}(r)$ several methods have been developed. In 1940 Herring suggested the method of orthogonalized plane waves. $u_{nk}(r)$ is expressed as a Fourier series but this contains many harmonics, since it has to be orthogonal to the wave functions of the valence electrons and the core electrons. The convergence is improved by starting from a wavefunction which is a linear combination of plane waves which already satisfies these conditions.

Somewhat earlier (1937) Slater suggested a representation of the wavefunction inside the atomic core by atomic wavefunctions, and between the atoms by plane waves, matching the two and taking into account the crystal symmetry. The convergence of this method is good.

Later Antonchik, Phillips and others simplified the method of orthogonalized plane waves considerably, replacing the orthogonalization by the introduction of a so-called pseudopotential $V(x, x') = \sum_i E_i\psi_i(x')\psi_i(x)$, where $\psi_i(x)$ is an atomic wavefunction, and E_i an atomic energy level. The problem reduces to the solution of the Schrödinger equation with the additional term $V(x, x')$ in the Hamiltonian.

In the calculation of the valence band the use of the one electron approximation is somewhat less justified. Strictly speaking the only possible basis for such calculations is the Hartree–Fock method. The correlation between the electron spins can be included partly by using an exchange pseudopotential. In 1951 Slater suggested replacing this by the exchange potential of free electrons with a density equal to the actual electron density at the given point. Slater's pseudopotential is proportional to $\rho^{1/3}$. It is being used for many problems because of its simplicity; however, it leads to considerable errors for low electron density. In general even the Hartree–Fock method does not fully allow for the correlations between states with opposite spins.

The electron correlations are in some measure taken into account in the method of valence bonds. The

wavefunctions are written as combinations of functions which describe the bonds between neighboring atoms. This method, which represents a known approximation in resonance theory appears to be the best procedure involving relatively simple calculations.

The paper by **V. A. Chaldyshev** and **A. S. Poplavnĭ** (Siberian Physico-technical Institute), "Shape of the Energy Bands of Some Compounds with Structures of the Zincblende," gives calculations of the valence band and conduction bands of the compounds GaAs and AlAs with the pseudopotential method. The crystalline potential is constructed from atomic Slater functions. Values are given for the width of the forbidden band; it amounts to 2.31 eV for GaAs and 2.82 eV for AlAs; the experimental values are 1.53 and 2.16 eV respectively.

V. G. Lyapin and **K. B. Tolpygo** (Kiev State University) presented a paper, "Study of the Structure of the Valence Bands of Crystals of Diamond Type," in which they describe the system of valence electrons by linear combinations of antisymmetrized products of separate σ bonds of which one has an electron missing. Nearest and next nearest neighbors are included. For each value of the wave vector $\mathbf{k}$ one obtains eight energy levels. For certain symmetry directions analytical expressions $E(\mathbf{k})$ are found for some branches throughout the Brillouin zone.

The theory gives identities between the values of the energy in three special points of the Brillouin zone and the three cyclotron constants. These are in satisfactory agreement with experiment.

The paper of **K. B. Tolpygo** and **D. I. Sheka** (Kiev State University), "Theory of Intrinsic Light Absorption in NaCl Type Crystals," uses a theoretical band structure calculated previously. The dispersion law is tabulated for an electron band with twofold degeneracy and three hole bands. One sums the probabilities for all transitions corresponding to a given frequency and thereby finds the intrinsic absorption of the crystal (outside the region of the exciton line) which is compared with experiment.

The paper by **A. I. Gubanov** (A. F. Ioffe Physico-technical Institute), "Damped Electron Waves in Crystals," deals with exponential decay in space of electron waves corresponding to forbidden values of the energy. Such waves can have application to calculations on the passage of current through a contact between two semiconductors of different type or through a thin dielectric layer, etc.

In the discussion following the rapporteur's lecture **V. M. Agranovich** drew attention to the importance of calculating Bose excitations in solids, since experimental data on this question had lately become available. K. B. Tolpygo remarked that there exists an exciton in the x-ray region (an electron from a deep level bound to its hole). É. I. Rashba raises a query about the paper of G. F. Karavaev, "Structure of the Energy Spectrum of Me_2Z_3 Compounds," asking what was meant by bands in a disordered system. K. B. Tolpygo remarked that there was a certain inconsistency in introducing bands in the presence of a random distribution of vacant sites in the lattice.

4. THEORY OF RECOMBINATION OF CARRIERS

The rapporteur was **V. L. Bonch-Bruevich.** Lately there has been growing interest in the theory of recombination because of the appearance of a great deal of experimental material. Cross sections for nonradiative recombination were found to cover a wide range of values from 10^{-13} to 10^{-20} cm^2 depending on temperature, impurities, and other factors. The accuracy of measurements in Ge and Si amounts to 30—40%. Cross sections of the order of 10^{-13}—10^{-15} cm^2 are of practical interest. The magnitude of σ depends non-trivially on the charge of the impurity. Four or five cases are known in which the capture cross section for an electron by a negative impurity is greater than for a neutral one. The temperature dependence is in general of the form $\sigma \sim T^{-n}$ with $2 < n < 4$, except for centers with a Coulomb repulsion. The theory must necessarily include three basic questions: (1) From what state does the capture take place, and how does it depend on the distribution function of the electrons? (2) How does the capture take place, what is the mechanism of energy transfer, and what part is played by phonons? Here it is not clear how to express the operator for the interaction of electrons with short-wave phonons. (3) What is the final state of the electron? Here one has to know the structure of deep traps for which so far one has only a hydrogen-like model. At present an accurate quantitative theory of recombination is still lacking. Theoretical papers are in general concerned with the determination of the temperature dependence of the recombination cross section and its order of magnitude. Calculations about the phononic and nonradiative transitions give cross sections which are by five orders of magnitude less than the experimental ones. The theory of cascade processes through highly excited states in a Coulomb field gives the required behavior with temperature. However, capture takes place also for neutral centers where there are no highly excited states. Evidently one has to consider multiphonon transitions.

É. P. Sinyavskiĭ (Applied Physics Institute of the Moldavian Academy of Sciences) had a paper, "Allowance for the Frequency Dispersion of Normal Oscillations in the Theory of Multiphonon Nonradiative Recombination. Non-Condon Approximation," which deals with homopolar crystals. By avoiding the Condon approximation he obtains a factor 100 in the recombination cross section.

In papers by **V. A. Kovarskiĭ** (Applied Physics Institute of the Moldavian Academy of Sciences), "Calculation of Recombination Coefficients at High Temperatures" and "Theory of Recombination Relaxation," the time dependence of the recombination is determined from the equation of motion for the density matrix. The

usual Hamiltonian of the electron phonon interaction is used as perturbation operator, but the number of particles in the band is not conserved. A multiphoton variant of the technique of Konstantinov and Perel' leads in first approximation to the usual formula for multiphoton transitions. The expansion parameter is estimated by comparing graphs of fourth and second (the first non-vanishing) order. The answer depends on the model for the trap. For a hydrogen-like model in an Einstein crystal including graphs of fourth order the recombination cross section is $\sigma \sim e^{-\Delta/kT}/(1+\gamma)$ where the expansion parameter $\gamma \sim Te^{-\Delta/kT}$, Δ being the depth of the trap. At high temperatures γ can approach unity and the temperature dependence then becomes weaker. Unfortunately there are no experimental data above the Debye temperature.

"Kinetic Equations for the Recombination Processes in a Quantizing Magnetic Field" by **V. A. Kovarskiĭ** and **I. A. Chaĭkovskiĭ** (Applied Physics Institute of the Moldavian Academy of Sciences) describes transitions between Landau levels and local impurity levels and investigates these. The irreducible parts of these equations give a graphic representation of the recombination coefficients. The effect of the magnetic field H on the trap is not included (no Zeeman effect). The presence of the field can extend the lifetime and suppress noise.

The paper by **E. M. Kuznetsova,** "The Influence of Damping on the Light Absorption in Semiconductors," considers the part played by phonons in radiative recombination. Owing to the interaction with phonons the states in the trap are not stationary, and this causes a broadening of the absorption edge.

"Problems of the Radiative Recombination at Impurity Centers in Silica" is a paper by **V. L. Bonch-Bruevich** and **A. A. Drugova** (Moscow State University). Experimental evidence shows that in silica there is radiative recombination on shallow acceptor levels which is accompanied by phonon emission. More phonons are emitted the shallower the acceptor. There are calculations on the relation between the intensity of optical and acoustic phonons.

5. EXCITONS AND SUPPLEMENTARY LIGHT WAVES

The rapporteur's talk was given by **S. I. Pekar** (Semiconductor Institute of the Ukrainian Academy of Sciences). He stressed that the term exciton is now understood to mean an elementary excitation which has at least one discrete quantum number. Up to 1957 it was believed that it was not essential to take account of space dispersion in crystal optics since it would give effects only of the order of $a/\lambda \sim 10^{-2}$ to 10^{-3}, where a is the lattice constant and λ the wavelength of the incident light. Space dispersion was taken into account only in those cases in which without it the effect would be completely absent (double refraction).

It was shown in 1957, however, that in the neighborhood of the exciton absorption band there are effects of the order of $(a/\lambda)(\omega_0/\omega - \omega_0)^{1/2}$ and these must necessarily be taken into account. As a result a number of authors carried out a consistent generalization of classical crystal optics, and this led to a number of interesting theoretical predictions, such as the violation of the Kramers–Kronig relations, the appearance of supplementary waves, etc.

S. I. Pekar discussed the experimental tests of the theory. In particular, as theory predicts, the shape of the exciton absorption line depends not only on the lifetime of the exciton, as is usually the case, but also on the thickness of the specimen. Here it is not possible to introduce a logarithmic decrement for the absorption, since the intensity of the light leaving the specimen is an oscillating function of the thickness of the specimen as a result of the interference of the additional waves with different refractive indices. Such experiments were carried out by Brodin, Gorban', and Timofeev. However, Davydov stated that the quantization of the wave vector and the energy due to the finite specimen thickness could lead to an oscillating behavior of the intensity of the transmitted light. V. I. Sugakov[4] showed that the discrete nature of the energy spectrum of excitons does not affect the refractive index of the electromagnetic waves and the additional boundary conditions on each face are the same as in the infinite crystal. The paper of **V. I. Sugakov** (T. G. Shevchenko State University, Kiev), "Quantum Theory of Electromagnetic Waves in Crystalline Plates," deals with the quantization of the energy levels of the crystalline plate + electromagnetic field system. The system is not homogeneous and its states cannot therefore be labelled by their momentum. The discussion is carried out without the Maxwell boundary conditions, which are automatically satisfied to an accuracy of $2\pi a/\lambda$. Near the exciton line there are several electromagnetic waves with different refractive indices, and the refractive index of each wave does not depend on the crystal dimensions even when the thickness is comparable with the light wavelenths. Then S. I. Pekar discussed in detail the question of the experimental study of exciton absorption spectra in CdS and ZnTe by Brodin and by Thomas and Hopfield and the theoretical explanation of their results. A paper of **A. A. Lipnik** proposes a new method of studying excitons. It consists in observing such exciton transitions in which the electron can be transferred from the lower conduction band to the higher one and thereby, for example, an exciton of the yellow band in Cu_2O becomes one in the blue band. Contrary to the situation in the usual exciton absorption band these lines will not be swamped by the intrinsic light absorption of the semiconductor. This experiment requires the presence of a considerable concentration of excitons (e.g., in the yellow band) and irradiation with infra-red light to cause the transitions. Calculation shows that the intensity of illumination should be of the order of 3 to 30 W/cm^2. The paper estimates

the photoionization cross sections for excitons in such transitions, which turn out to be of the order of 10^{-13} to 10^{-15} cm^2 both for Cu_2O and for CdS.

A joint paper by **V. M. Agranovich** and **V. L. Ginzburg** presented at the plenary session discussed the following problems.

1. The behavior of the real and imaginary parts of the refractive index in a gyrotropic medium allowing for space dispersion and damping. Results were given for $n(\omega)$ and $\kappa(\omega)$ for all three normal waves. It was shown that in a gyrotropic medium the inclusion of damping also changes the behavior of $n(\omega)$ and $\kappa(\omega)$ qualitatively in the neighborhood of the resonance.

2. The behavior of the angle of rotation of the plane of polarization in the neighborhood of the exciton quadrupole lines. The discussion of the natural rotating power is usually carried out by expanding the tensor $\epsilon_{ij}(\omega, k)$ in a power series of the wave vector:

$$\varepsilon_{ij}(\omega, \mathbf{k}) = \varepsilon^0_{ij}(\omega) + i\gamma_{ijl}k_l.$$

However, the tensor $\gamma_{ijl}(\omega)$ shows a resonance near the exciton lines only if these lines belong to dipole excitons. Near quadrupole resonance lines the resonance includes the following terms:

$$\alpha_{ijlm}k_lk_m + i\gamma_{ijlmn}(\omega)\, k_lk_mk_n,$$

and only the second of these terms contributes to the rotation. If one takes this circumstance into account one finds, for example for cubic crystals, an expression for the specific rotating power of the form

$$\varphi = \frac{\omega}{2c}\left(f_0 + \frac{f_1}{\omega - \omega_1}\right),$$

where ω_1 is the frequency of the quadrupole resonance and $f_0 \sim d/\lambda_0$ and $f_1 \sim \omega_1(d/\lambda_0)^2$ ($\lambda_0 = 2\pi c/\omega$ is the light wavelength in vacuo). Hence, for frequencies ω for which

$$\frac{|\omega - \omega_1|}{\omega_1} \leqslant \frac{d}{\lambda_0} \sim 10^{-2} - 10^{-3},$$

the resonance term gives a contribution of the same order as that coming from dipole exciton states and probably can be observed.

3. Theory of dipole states of surface excitons based on a macroscopic approach (paper by V. M. Agranovich and Yu. V. Konobeev). It is shown that the polarization and frequency of surface excitons can be determined from the macroscopic Maxwell equations if one takes into account the space dispersion of the tensor $\epsilon_{ij}(\omega, \mathbf{k})$. If retardation is neglected then for surface excitons with an electric field intensity $E \neq 0$, $\epsilon_{ij}(\omega, \mathbf{K})K_iK_j = 0$, whereas for excitons with $\mathbf{E} = 0$ $|\epsilon^{-1}_{ij}(\omega, \mathbf{K})| = 0$ where $\mathbf{K}$ is the complex "wave vector" of the surface exciton. For the treatment of excitons with $E = 0$ one requires additional boundary conditions.

4. The theory of non-linear effects in the exciton region of the spectrum (paper by V. M. Agranovich, Yu. V. Konobeev and L. N. Ovander). In the exciton region of the spectrum the total Hamiltonian of the crystal is $H = H_{Coul} + H_{phot} + H_{int}$ where H_{Coul} is the crystal Hamiltonian without retardation, H_{phot} the Hamiltonian of the transverse photon field and H_{int} the operator for the interaction between photons and charges. If B and B^+ are Bose fields corresponding to the annihilation and creation of "Coulomb" excitons and A and A^+ are Bose operators for photons then H_{Coul} contains terms which are quadratic in B and B^+ and also cubic and higher order terms. H_{int} contains terms of the form A^+B, AB^+ and also A^+BB etc. whereas H_{phot} is quadratic in A and A^+. If one collects in H only the quadratic terms and diagonalizes the corresponding quadratic form one finds the states which correspond to solutions of the Maxwell equations in the medium. The presence of the anharmonic terms which have been mentioned leads to non-linear effects which have been investigated to first order of perturbation theory. It is shown that the anharmonicity in the Coulomb part of the system contributes substantially to the intensity of non-linear processes. These intensities do not diverge for any values of the frequency ω even if damping is neglected contrary to the result one usually obtains in applying perturbation theory for a Coulomb subsystem interacting with an external electromagnetic wave.

The paper by **M. I. Shmiglyuk** and **S. A. Moskalenko** (Applied Physics Institute of the Moldavian Academy of Sciences) considers the question of the structure and symmetry of the bands in crystals of the Wurtzite type at the point $\mathbf{k} = 0$, allowing for the fact that the unit cell contains two molecules. It is found that the 5s state of the Cd^{++} gives rise to two electron bands with the symmetries Γ_7 and Γ_8, and the 3p state of S^{--} gives six hole and $2\Gamma_9$, $2\Gamma_7$ and $2\Gamma_8$. They find the possible exciton levels for $n = 1, 2, 3$, where polarization and activity with and without a magnetic field and study the vibration spectrum of the lattice. In the discussion **V. M. Agranovich** remarked that the results are particularly interesting in connection with the experiments of Hopfield and Thomas on CdS, and **V. V. Sobolev** noted that the experiments agree with theory also for other materials of the Wurtzite type.

6. IMPURITY LIGHT ABSORPTION AND LUMINESCENCE

The rapporteur's talk was given by **Yu. E. Perlin.** Particular attention has recently been given to phononless transitions which give narrow absorption peaks. They are particularly well observable in conditions of weak heat release but can be observed also in the presence of strong heat release when the phonon absorption occurs sufficiently far in relation to the width of the phononless peak. The interest in these transitions is due to three basic causes: (1) the development of experimental techniques which made the observation possible, (2) the discovery of the Mössbauer effect

i.e., of phononless transitions with the emission of γ rays, and (3) the occurence of such transitions in admixtures of transition elements or rare earths in laser systems.

In the sectional meeting on "Theory of Impurity Semiconductors" **M. A. Krivoglaz** (Metal Physics Institute of the Ukrainian Academy of Sciences) gave a lecture "On the Theory of the Broadening of Phononless Lines in Mössbauer and Optical Spectra." The anharmonicity may reduce by several orders of magnitude the broadening caused by the interaction with local vibrations, since the anharmonicity averages the transitions over many lines. **Yu. E. Perlin** remarked that this is a departure from the Condon approximation.

V. V. Khizhnyakov (Institute of Physics and Astronomy of the Estonian Academy of Sciences) gave a paper on "The Influence of Anharmonicity on the Quasi-line Structure of Electron-vibrational Spectra and the Mössbauer Effect," in which double-time Green functions are used to calculate the intensities, positions and widths of quasi-lines connected with corresponding transitions of localized vibration modes. The temperature broadening and shift of these quasi-lines depends on their number, the strength of the electron-phonon interaction and the energy of the quanta.

The paper by **I. P. Ipatova** and **A. A. Klochikhin** (Physico-technical Institute of the U.S.S.R. Academy of Sciences), "One-phonon Impurity Absorption in the Lattice of a Homopolar Crystal with Diamond Structure," obtains by means of thermal Green's functions the temperature dependence of the absorption connected with the damping of the emitted phonons because of the anharmonicity of the lattice vibrations. The temperature dependence should appear at temperatures below the Debye temperature. This explains the observation by Smith and Taylor of a noticeable temperature dependence of the one-phonon impurity absorption in a diamond semiconductor at temperatures between 83 and 295°K.

Yu. E. Perlin then gave a brief review of the state of the theory of F centers which cannot yet be regarded as complete. The formulae of the continuum theory of S. I. Pekar for the total intensities of absorption and luminescence are very sensitive to violations of the condition of large radius. Hence in the case of alkali-halide crystals they are reduced by a factor 2 or 3. The temperature dependence of the half-width of the F band is such that the characteristic phonon frequency turns out to be considerably less than the Debye frequency, which indicates the presence in the F center of low-frequency localized vibrations. The paper of **O. I. Sil'd** (Institute of Physics and Astronomy of the Estonian Academy of Sciences), "A Vibrational Model for the Treatment of Electron-vibration Spectra of Luminescence Centers of Small Dimensions," considers the question of reducing the number of variables. The temperature dependence of the effective frequencies is determined by the width of the frequency interval of normal vibrations with which the vibrations of the model can interact.

7. THEORY OF SEMICONDUCTORS WITH LOW MOBILITY

The *rapporteur's* talk was given by **Yu. A. Firsov** (Semiconductor Institute of the U.S.S.R. Academy of Sciences). The problem of semiconductors of low mobility arose in connection with the need to explain the exponential rise of the mobility at high temperatures which was found by a number of authors in the oxides of the transition elements, and from the fact that the usual methods of calculation, for example that using a Boltzmann equation are not applicable since they cannot give values for the mobility less than 1 cm^2/volt sec. This critical value comes from the condition of the applicability of the Boltzmann equation

$$\frac{\hbar}{kT} \ll \tau, \tag{6}$$

and since $\mu = e\tau/m^*$ this implies

$$\mu \gg \frac{\hbar e}{kTm^*} = 20\frac{m}{m^*}\frac{500}{T}.$$

Here μ is the mobility, m^* and m the effective mass and the free-electron mass respectively. One can try to make the problem easier by assuming very narrow separated bands, i.e., bands with $\Delta E \lesssim kT$. However, even in that case the condition (6) must in practice be satisfied. For polarons of large radius S. I. Pekar has shown that the scattering of polarons can be a one or two-phonon process. This result was based on adiabatic perturbation theory which is not applicable to the case of strong interaction, and this makes it impossible to obtain too low a value for the mobility.

In the following we shall be concerned with a model in which the current carriers are polarons of small dimensions. It will be clear that in such a model the mobility of the carriers can be very small. The condition for the existence of small polarons takes the form that $\eta_1 = I/E_p$ where I is the overlap integral and E_p is the polaron shift.

The inapplicability of the Boltzmann equation to this problem is not limited to the theory of low mobility. A similar situation arises also in the theory of the transverse part of the electric conductivity tensor in a quantizing magnetic field.

The problem of the motion of a polaron of small dimensions was first considered by Yamashita and Kurosawa[5], who calculated the transition probability of an electron from one site to another in the presence of a strong interaction with the phonons causing the polarization, and they showed that this probability, and therefore the mobility, behaves as an activation process. Holstein[6] solved the same problem and showed that the result of Yamashita and Kurosawa can be obtained only if one allows for the dispersion of the pho-

nons. He showed that the electric conductivity consists of two contributions, of which one is due to electrons jumping whereas the other is a band motion of the polarons.

He showed that in addition to the condition $\eta_1 \ll 1$ it is also necessary to satisfy the condition $\eta_2 = I^2/(E_a kT)^{1/2}\hbar\omega_0 \ll 1$ where E_a is the activation energy and ω_0 the limiting frequency of the phonons producing the polarization. Thus a further parameter appears in the theory. At high temperatures, $T \gg \Theta$ where Θ is the Debye temperature, the first mechanism dominates and gives a temperature dependence involving an activation energy

$$W = \omega_0 \eta_2 e^{-\frac{Ea}{kT}}$$

where

$$\mu = \mu_0 \frac{\hbar W}{kT},$$

represents the probability per unit time of an electron jumping to a neighboring site; on the other hand for $T \ll \Theta$ the main contribution to the mobility comes from the band motion of the polaron:

$$\mu = \frac{\langle v_x^2 \rangle}{kTW_n^{(0)}},$$

where $\langle v_x^2 \rangle$ is the mean square velocity of the electron and $W_n^{(0)}$ is the probability of scattering, calculated to lowest order in I.

The small value of the mobility in the low-temperature region is due to the fact that the polaron effect substantially narrows the conduction band, and therefore increases the effective mass. Therefore the electric conductivity has a minimum near a certain critical temperature T_0 of the order of the Debye temperature. However, since Holstein derived his theory essentially from intuitive arguments, it was still necessary to find an exact derivation of the expression for the conductivity from first principles (e.g., using the Kubo formula) and to find out what parameters enter in the theory. The first papers on this subject after Holstein were those of Nagaev[7], Dogonidze and Chizmadzhiev[8], Dogonidze, Chernenko and Chizmadzhiev[9], and Klinger[10]; the latter first posed the question how to derive the electric conductivity from the Kubo formula; Lang and Firsov[11] succeeded in developing a perturbation theory for a problem involving strong coupling of the electrons to the virtual phonon. The Kubo formula was evaluated by means of the technique of Konstantinov and Perel'. The following were the basic results:

1. The results of Holstein for the electric conductivity at high temperatures were confirmed.

2. The parameters in this theory have the values indicated by Holstein.

3. The low-temperature result of Holstein is incorrect since the expression used by Holstein for the probability $W_n^{(0)}$ is not the leading term in the perturbation series. For the same reason the definition of the temperature T_0 is also changed.

Friedman and Holstein[12] have studied a simple model and shown that the Hall mobility behaves at $T > T_0$ like $e^{-Ea/kT}$.

On the other hand Firsov[13], who starts from the Kubo formula, using a technique he had previously developed jointly with Lang, showed that for $T > T_0$ the Hall mobility behaves as $e^{Ea/kT}$. The paper by **E. K. Kudinov** and **Yu. A. Firsov**, "Optical Interband Transitions in Semiconductors with Low Mobility," considers the light absorption due to interband transitions in semiconductors with low mobility. The absorption curve has a maximum which for $T > T_0$ is of Gaussian form with a width of the order $(E_p kT_0)^{1/2}$, while for $T < T_0$ the width is of the order $(E_p\hbar\omega_0)^{1/2}$. In addition, one finds near the long-wave edge of this maximum a sharp phononless peak analogous to the Mössbauer peak, with a total intensity proportional to e^{-S_T}, where S_T is a number of the order of the dimensionless electron phonon coupling constant. The width of this peak depends on the collision probability which occurs in the Boltzmann part of the conductivity.

8. THEORY OF RESONANCE PHENOMENA. MAGNETIC PROPERTIES OF SEMICONDUCTORS

The rapporteur's talk was given by É. I. Rashba (Semiconductor Institute of the Ukrainian Academy of Sciences). The paper of **G. L. Bir** (Semiconductor Institute of the U.S.S.R. Academy of Sciences), "Intensities of Allowed and Forbidden Lines in Electron Paramagnetic Resonance," considers the intensities of allowed and forbidden hyperfine components of the EPR spectrum. The spin Hamiltonian is taken in the form

$$H = g_{\alpha\beta}\hat{S}_\alpha H_\beta + A_{\alpha\beta}\hat{S}_\alpha \hat{I}_\beta + V_{cr},$$

where $\hat{S}_\alpha$ and $\hat{I}_\alpha$ are the spin operators of the electrons and the nuclei, and the tensors g and A represent the g factor and the hyperfine interaction. V_{cr} is an operator describing the effect of the crystalline field. To zeroth order in A the eigenfunctions of the Hamiltonian have the form $\Psi_{l,M}\varphi_m^{(M)}$ where $\Psi_{l,M}$ are the eigenfunctions of the electron part of the operator $g_{\alpha\beta}S_\alpha H_\beta + V_{cr}$ and $\varphi_m^{(M)}$ are the nuclear spin functions. The axis of quantization of the nuclear states is chosen not in the direction of the external field, but in the direction of the effective field $H_{eff} \sim A_{\alpha\beta}(\Psi_{l,M}|S_\beta|\Psi_{l,M})$ which is defined in terms of the hyperfine interaction constant and depends on the electron state and the angle between the direction of the external field and the axes of the crystalline field. Since the axes of quantization of the nuclear spin functions are different for the initial and final electron states involved in the electron resonance transition, there appear so-called forbidden lines with the selec-

tion rule $\Delta m \neq 0$. Formulae are obtained for the intensity of these lines and for their variation with angle. Experimental data for the EPR of Mn^{+2} in $SrCl_2$ and for Fe^{+2} in CaF_2 are in good quantitative agreement with the theory. A paper by **G. E. Gurgenishvili** and **G. R. Khutsishvili** (Physics Institute of the Georgian Academy of Sciences) gives calculations of the relaxation time for the nuclear spins in semiconductors and metals caused by a contact interaction of nuclei with conduction electrons in a strong magnetic field in which the space quantization of the electron motion becomes important. The cases of a highly degenerate and a non-degenerate electron gas are considered. In the first case it is shown that the relaxation rate shows oscillations which arise from the singularities in the density of states of the conduction electrons. However, an experimental detection of these oscillations would seem rather difficult because experimental determinations of the relaxation time are rather rough. A paper by **V. I. Sheka** (Semiconductor Institute of the Ukrainian Academy) studies the peculiar features of higher order resonances, which appear because the dispersion law of the electrons is not quadratic. The dependence of the g factor on the wave vector leads to the appearance of isotropic terms in the intensity of two bands of such resonances, together with an anisotropic part caused by the spin-orbit degeneracy of the bands: the interaction of the conduction band with the nearest valence band is taken into account, and the isotropic part of the resonance intensity is determined from the band structure parameters. As usual, the combined absorption exceeds the paramagnetic one. The paper by **S. I. Pekar** and **É. I. Rashba** (Semiconductor Institute of the Ukrainian Academy), "Combined Resonances in Crystals in Non-uniform Magnetic Fields," considers the spin transitions of the carriers in semiconductors caused by the electric field of the electromagnetic wave. The coupling of spin and orbital degrees of freedom is caused by the non-uniformity of the static magnetic field, which can be due either to a lack of uniformity in the external field or to the spontaneous field of a ferromagnet or antiferromagnet. If, in the first case, the external field varies sufficiently smoothly, the intensities of the combined resonances are two to three times greater than those of the paramagnetic resonance. In the second case one has to take into account the interaction of the spin of a given electron with the magnetic field of the spin and orbital moments of the other electrons. A canonical transformation is found which leads to an effective-mass Hamiltonian; this is possible because the magnetic field $\mathbf{h}(\mathbf{r})$ has the periodicity of the crystal lattice and the magnetic energy $\beta_0 h$ is small compared to the interband distance. The intensity of combined resonances will then be 10^5 times that of the paramagnetic resonance.

A number of papers deal with problems arising from the theory of kinematic problems in ferromagnets and antiferromagnets. In the paper of **E. L. Negaev**, "On a Spin Mechanism for Charge and Energy Transport," a quasi-homopolar model is used to calculate the kinetic coefficients for compounds of the transition elements. The technique consists in using the Kubo formula together with the Bogolyubov projection method in perturbation theory. One finds expressions for the heat current operator for d-electrons projected on the subspace of quasihomopolar functions. Together with the projected electric current this makes it possible to calculate the conductivity, thermoelectric effect, and thermal conductivity of the crystal due to the d-electrons. In the paramagnetic state the conductivity is inversely proportional to the temperature and can reach 10^2 ohm^{-1} cm^{-1}. In the antiferromagnetic state, when the scattering is predominantly by imperfections the conductivity does not depend on temperature. The thermo-electric e.m.f. grows with decreasing temperature and can reach hundreds of microvolts.

The paper by **Sh. Sh. Abel'skiĭ** and **Yu. T. Irkhin** (Metal Physics Institute of the U.S.S.R. Academy of Sciences), "Spontaneous Hall Effect and the Scattering Mechanism in Ferromagnetic Semiconductors," gives expressions which connect the magnetic part of the electric resistance and the Hall coefficient (both spontaneous and normal) for non-degenerate ferromagnetic superconductors with one type of carriers. It is assumed that the main mechanism of scattering is the scattering by spin inhomogeneities. The paper of **A. M. Kosevich** and **L. V. Tanatarov** studies the effect of a one-dimensional perturbing potential on the structure of the energy spectrum of electrons with a quadratic dispersion law in a magnetic field. It is shown that such a model can be used to analyze the effect of a dislocation in a crystal on the scattering of electrons passing close to its axis.

9. ACOUSTIC EFFECTS IN SEMICONDUCTORS

The rapporteur's talk was given by **V. L. Gurevich** (Semiconductor Institute of the U.S.S.R. Academy of Sciences). Acoustic effects in semiconductors have recently attracted attention not only because they allow one to study a number of physical properties, but also because of the possibility of amplification of ultrasound and of making an ultrasound generator using a semiconductor in a constant electric field. For the physics of semiconductors the most interesting amongst these acoustic effects are those which depend on the interaction of sound with the conduction electrons: (1) sound absorption, for which the lattice and electron contributions can easily be distinguished in photoconductors and by applying electric or magnetic fields; (2) the variation of the sound velocity with various physical parameters; (3) the electroacoustic effect, which is entirely due to the interaction of sound with the conduction electrons. The last effect consists in

the appearance of a constant "electro-acoustic" current j^{ac} on the passage of a sound wave. The idea of this effect was first suggested by Parmenter[18]. Excluding, for the present, piezo-electric semiconductors, in which deformations cause long range macroscopic electric fields, one can show that the electro-acoustic effect is large in those semiconductors in which there are several kinds of electrons characterized by different deformation potentials, so that the difference between the deformation potential of a given electron and the average value for all electrons does not vanish. (This happens in such semiconductors as n-Ge or n-Si, in intrinsic semiconductors, and in semiconductors with touching bands.) The last condition is necessary but not sufficient for the appearance of strong electro-acoustic effects. It is also necessary that the sound wave should disturb the equilibrium of the electronic system. There must also exist processes which have a large relaxation time so that the equilibrium is disturbed in respect of those processes in particular. In semiconductors with many energy minima the scattering from one minimum to the other is a process of this kind, and in intrinsic semiconductors it can be the electron-hole recombination. (In semiconductors with touching bands such processes do not exist and therefore the electro-acoustic effect in these is very small.) The paper by **S. V. Gantsevich** and **V. L. Gurevich** (Semiconductor Institute of the U.S.S.R. Academy of Science), "Theory of Electro-Acoustic Effects in Semiconductors of the Type of n-Germanium," considers the elastic (impurity) and inelastic (phonon) scattering of electrons between minima. In this the dependence of j^{ac} on τ_i/τ_e was found where τ_i is the relaxation time of electrons within a given minimum and τ_e the relaxation time between minima. In the presence of an external magnetic field a new quantum effect appears—an oscillation of j^{ac} as a function of H. This effect is in fact a generalization of the magnetophonon resonance predicted by V. L. Gurevich and Yu. A. Firsov[14] to the case of interminimum scattering. Since the nature of the oscillations and their period depends on the ratio of τ_i to τ_e, the study of this effect could allow one to obtain information on various mechanisms of relaxation in semiconductors of the type n-Ge and n-Si, and this applies to the investigation of magneto-acoustic effects generally. The influence of external fields on the electro-acoustic effect is considered in two further papers presented to the conference: **A. A. Grinberg** and **N. I. Kramer** (A. F. Ioffe Physico-technical Institute), "Magneto-Acoustic Effect in Semiconductors and Piezo-electrics," and **V. D. Iskra** (University of Chernovtsy), "Amplification of the Electro-acoustic Effects in Weak Magnetic Fields." The idea of the first paper is the following: If a sound wave passes through a semiconductor at right angles to an applied magnetic field, then a potential difference appears in the direction perpendicular to both. This is due to the fact that the electrons and holes which are excited by the sound wave are deflected in different directions by the magnetic field and therefore create a potential difference (short-circuit current). The problem is solved for the case of intrinsic semiconductors and piezo-electrics for $kl \ll 1$, where k is the wave vector of the sound wave and l the mean free path. In the case of the piezo-electric the electro-acoustic field can amount to 0.1 V/cm. The paper by **V. D. Iskra** suggests a method for amplifying the electro-acoustic effect. If a semiconductor through which sound waves are transmitted is placed in crossed electric and magnetic fields at right angles to the propagation of sound then one can compensate the Hall current caused by **E** and **H** by the electro-acoustic current. It turns out that in a weak magnetic field the compensating field exceeds the intensity of the electro-acoustic field two or three times.

In piezo-electrics the propagation of sound causes macroscopic fields with the space and time periodicity of the sound wave. These fields give rise to electron currents, i.e., the distribution of electrons lags in phase behind the potential of the sound wave because of the finite conductivity of the semiconductor. The Joule heat produced by these currents is exactly equal to the mechanical energy dissipated in the sound wave. In piezo-electrics one finds also a strong electro-acoustic effect which can reach several V/cm. White[15] suggested setting up a state in which the electron density is ahead of the sound wave in phase through the action of an electric field. In that case one should find not an absorption but an amplification of the sound provided $v > \omega$, where v is the electron drift velocity in the electric field and ω the phase velocity of the sound wave. This is indeed found in a number of experimental papers on piezo-electrics, showing: (1) sound amplification, (2) generation of acoustic noise. Since the instability criterion is independent of the piezo-electric parameters, the amplification is possible also in substances which are not piezo-electric. In a paper of **É. M. Épsteĭn** (Institute of Radio Engineering and Electronics of the U.S.S.R. Academy of Sciences), "On the Theory of Sound Amplification in Semiconductors," it is shown that the instability appears in piezo-electrics at $v \gtrsim \omega$ only when: (1) the absorption by the lattice is small, (2) the symmetric part of the electron distribution function is of the Boltzmann type, (3) the electron relaxation time is independent of energy. If the first two conditions are satisfied and the third one is violated the value of the critical drift velocity begins to vary with the sound frequency, the temperature and the effective mass. The paper also studies the instability criterion in the case of heated electrons.

The existing theory of sound amplification is White's linear theory of sound amplification in a single passage. It is important to work out a theory of sound amplification in multiple passage, when interference effects become important. A paper by **V. L. Gurevich**

and **V. D. Laĭkhtman** (Semiconductor Institute of the U.S.S.R. Academy of Sciences), "Non-linear Effects Limiting the Sound Amplification in Piezo-electrics," shows that the maximum amplification takes place when an interference condition is satisfied: the phase of the wave which is transmitted in the forward or backward direction must coincide with the phase of the primary wave. The amplification may then substantially exceed the single-passage amplification and the system may start generating sound with a wavelength of the order of the Debye radius. The linear theory gives naturally unlimited amplification. However, there are always non-linear effects, which will limit the amplitude. In the same paper it is shown that the amplification of progressive waves is dominated by the non-linearity due to the electrons. The amplification factor then begins to depend on the amplitude of the wave, and a wave will form in the crystal which travels without increase or decrease in its amplitude. There are two mechanisms for the formation of such a stationary wave: (1) For weak super-criticality the rise in amplitude is accompanied by a decrease in the screening of the piezo-electric fields by the free carriers, and as a result the sound velocity increases, approaching the sound velocity in a dielectric as long as the condition $v = \omega$ is not yet satisfied. When this happens $\Gamma = 0$, and the wave becomes stationary. (2) At high super-criticality the lattice absorption plays an important part. It is shown that, as the amplitude increases, the energy transmitted to the system by the external field tends to a constant limit, while the energy lost to the lattice increases indefinitely. The stationary amplitude is determined from the condition of equality of these two rates. The paper also deals with the problems arising in the non-linear theory of standing waves. The stationary amplitude is determined for that case.

The rapporteur, **V. L. Gurevich,** also discussed the question of the intensity of acoustic noise in the region of acoustic instabilities. In piezo-electrics the acoustic instability has a convective character, and the amplitude may therefore be limited not only by non-linear effects, but also by the dimensions of the specimen. If in this case the dimensions stop the growth of fluctuations at such a level that the non-linear effects are not yet significant, the linear theory is satisfactory.

The paper by **V. L. Gurevich** and **V. D. Kagan** (Semiconductor Institute of the U.S.S.R. Academy of Sciences), "Growth of Fluctuations in Piezo-electrics Under Conditions of Acoustic Instability," deals with Rayleigh scattering of light in the region of acoustic instability when the linear theory is still applicable. It is shown that the intensity of scattered light under conditions of instability may exceed the intensity of scattering in thermodynamic equilibrium by a factor of 2 or 3. The electro-acoustic current caused by the propagation of growing fluctuations is also calculated. This current has to be subtracted from the ohmic current and this explains the bend in the voltage-current characteristic observed by Smith[16].

In the meeting on "Instability Effects and Lasers" there were reports on two papers whose subjects were closely related to the topic. A paper of **Sh. M. Kogan** and **V. B. Sandomirskiĭ** (Institute of Radio Engineering and Electronics of the U.S.S.R. Academy of Sciences) investigates the amplification of ultrasound in a piezo-electric dielectric by means of a beam of charged particles moving through a gap in the dielectric. In the absence of interaction there would be two independent waves: a plasma wave in the beam and an elastic wave in the piezo-electric. The interaction, which turns out to have a resonance character and which is due to the penetration of the field of the plasma wave into the piezo-electric and vice versa, couples these waves and shows a maximum when the plasma and elastic waves have the same frequency and the same wavelength. The amplification factor at the maximum is proportional to $\chi^{2/3}$ for volume waves, where χ is the electro-mechanical constant and to $\chi^{1/2}$ for surface waves.

The paper of **Yu. V. Gulyaev, V. I. Pustovoĭt** and **P. E. Zil'berman** (Institute of Radio Engineering and Electronics of the U.S.S.R. Academy of Sciences) considers two problems: (1) the amplification of surface waves in adjacent layers of a piezo-electric and a semiconductor, (2) the reduction of the energy dissipation in a piezo-electric accompanying the amplification of ultrasound. The latter arises from the fact that the current passes through a semiconductor with a very high mobility. Since the power dissipation is $W \sim 1/\mu$, where μ is the mobility, the value of W in a system containing a piezo-electric material and InSb is of the order of 30 W/cm^2, much lower than for a bulk piezo-electric. A paper by **G. Yu. Buryakovskiĭ, V. L. Vinetskiĭ, V. S. Mashkevich,** and **T. M. Tomchuk** (Physics Institute of the U.S.S.R. Academy of Sciences) considers the theory of a homogeneous semiconductor laser using several variants of induced transitions. For a system consisting of three carriers and excitons in equilibrium with the carriers it is shown that: (1) it is impossible to obtain induced transitions from direct or indirect interband transitions, (2) an increase in the impurity concentration increases the binding between the current carriers and the excitons, and thereby worsens the conditions for obtaining a laser effect from interband transitions. In the absence of equilibrium between excitons and the carriers neither of these statements applies. The authors considered the question whether a laser effect could be produced in direct exciton transitions, allowing for the fact that the excitons are not exactly bosons. It is shown that the threshold of such a laser would be considerably lower than that for a laser based on direct interband transitions. The theory has been worked out quantitatively. It leads to expressions for the threshold for

laser emission in all the models considered, including a laser based on transitions between bands and impurity states.

10. THEORY OF LATTICE VIBRATIONS

The rapporteur's talk was given by **N. N. Kristofel'** (Institute of Physics and Astronomy of the Estonian Academy of Sciences). In the last few years the dynamics of crystal lattices has had its second youth. This was due to three causes. Firstly, new and very effective experimental techniques became available for the determination of the vibrational spectra of solids. It is now possible to compare the theory of vibrations with experiment, and this shows up its weaknesses and encourages further refinement. Secondly, lattice vibrations play an essential part in many processes of practical importance (relaxation phenomena, electron-phonon transitions, the Mössbauer effect, infra-red absorption, etc.). Thirdly the study of the dynamics of imperfect crystals, and the excitation of their vibrations in all these processes, acquired particular significance.

The first part of the report was concerned with perfect crystals. The dispersion curves which have recently been determined experimentally,for many crystals by slow-neutron scattering have shown that the Born theory, which regards the atoms in the crystal as point particles, is inadequate. A shell model of a crystal, which has recently been developed, increases the number of degrees of freedom and makes it possible to represent the experimental data with far fewer parameters. K. B. Tolpygo and his co-workers have over the years developed a quantum-mechanical theory of lattice dynamics which has contributed a greater physical clarity and theoretical rigor than the shell theory, which is a special case of it. A paper by **K. B. Tolpygo** and **E. N. Korol'** (Kiev University), "A Study of the Long-wave Vibrations of Crystal Lattices of the ZnS Type," applies this theory to crystals with intermediate coupling. An electron pair which binds two neighboring atoms may belong to either of them, or form a σ bond, and this leads to the appearance in the theory of fractional charges, which can vary in the course of the vibrations. A long-wave approximation then gives three acoustic branches $\omega(\mathbf{k})$. Expressions are also obtained for the elastic constants and the parameters of the piezo-electric tensor. There are also results for the limiting frequencies of optical vibrations, and for the dispersion law in the infrared region.

In a paper, "The Effect of Ion Polarizability on the Equation of State of Ionic Crystals of NaCl and CsCl Type," **V. A. Kuchin** (Siberian Physico-technical Institute) has generalized the model of K. B. Tolpygo to include the effect of a uniform hydrostatic pressure in a quasi-harmonic approximation. He considers the change in the polarizability, the effective charges, the vibration frequencies, and the elastic constants. The model of polarizable ions agrees better with experiment, particularly at high pressures, than the point-like particle model.

A contribution by **A. A. Nran'yan** (Physico-technical Institute of the U.S.S.R. Academy of Sciences), "Effects of Deformations on the Frequency Spectrum of Lattice Vibrations," investigates the effect on the spectrum of various uniaxial deformations using the Blackman model. The Grüneisen approximation is justified only for a deformation along a three-fold axis. Upon compression both maxima in the phonon spectrum are lowered and displaced. The main one towards shorter waves and the secondary one towards long waves. Upon extension the maxima are also reduced, the frequency density between them is increased and both are displaced towards longer waves the displacement of the main maximum being greater.

The contribution by **V. S. Oskot-skiĭ** "On the Negative Thermal Expansion Coefficient in Germanium," deals with the dependence of the thermal expansion on temperature. The model used for the vibration spectrum is based on the neutron scattering data. The Grüneisen constant for the long-wave vibrations is determined from the measured dependence of the elastic constants on pressure, while the Grüneisen constants for the high-frequency vibrations are treated as parameters in the theory. The theoretical curve lies between two available experimental curves. For temperatures between 15 and 40°K the thermal expansion is negative; at lower temperatures it reaches a positive maximum and then tends to zero as T^3.

The contribution by **B. A. Tavger** and **V. Ya. Demikhovskiĭ** (Gor'kiĭ University), "Phonons in Films," contains a phenomenological study of the dispersion law in a uniform layer with free edges. There exist symmetric and antisymmetric transverse vibrations in the plane of the layer and "mixed" vertical vibrations. The dispersion curves were analyzed with an electronic computer. The density of states for the film is found. If $2lT \gg \Theta a$, where $2l$ is the film thickness, a the lattice constant and Θ the Debye temperature, the results are the same as for bulk material. In the opposite limit the results are the same as for bulk material for the lower branch and small wave vectors. Otherwise surface effects have to be corrected for.

Another paper by the same authors, "Electron-phonon Interaction in Thin Semiconducting Films," considers the scattering of electrons at low temperatures using the deformation potential method. The relaxation time in the film is proportional to its thickness, and, in a narrow range of the relevant parameters this, and therefore the conductivity, is less than in bulk material.

The second part of the report by N. N. Kristofel' concerned the theory of imperfect crystals. The theory of lattices with defects has been studied intensively for a relatively short period following the pioneer work of I. M. Lifshitz. The theoretical discus-

sion of the problem started with calculations of various academic models, particularly chains with point defects, and with the analysis of the most general conclusions from general theorems; eventually this led to a complete description of the general character of the effect of defects on the vibration spectrum of crystals. For three-dimensional lattices and realistic systems the theory had until recently not been carried very far. Recently the theory has made considerable progress as regards the effects of local vibrations on various processes such as the electron-vibrational transitions, infra-red absorption, the Mössbauer effect, complex scattering, spin-lattice relaxation, etc. **G. S. Zavt** and **N. N. Kristofel'** (Institute of Physics and Astronomy of the Estonian Academy) have developed a theory for calculating the frequencies of local vibrations near an isotopic defect of anion or cation in a three-dimensional binary ionic crystal. The parameters in the secular equation for the local frequencies depend on moments of the phonon spectrum of the perfect crystal. The calculation also gives the critical mass of the impurity for which local modes appear. For NaF, KCl, RbBr, and RbI the mass of the impurity must be about half of that of the atom it replaces.

G. S. Zavt (Institute of Physics and Astronomy of the Estonian Academy) in a paper "Theory of Thermal Conductivity by Phonons (the case of strong phonon-defect interaction)," calculated the thermal conductivity κ from the general theory of irreversible processes without using perturbation theory or a Boltzmann equation. In the case of heavy impurities, which give rise to pseudolocal modes of low frequency, the thermal conductivity at temperatures corresponding to such frequencies should go down considerably. In the case of light impurities the thermal conductivity should rise above the value given by the theory of Clemens.

11. PHENOMENOLOGICAL THEORY OF SEMICONDUCTORS

The rapporteur's talk was given by **Z. S. Gribnikov** (Institute of Metallurgical Problems of the Ukrainian Academy). He summarized a number of contributions to the conference.

The paper by **O. S. Zinets, G. P. Pek,** and **Yu. I. Karkhanyan** (Kiev University), "Some Problems of the Theory of Electroluminescence," considers the effect of an electric field applied to the surface of a semiconductor on the intensity of luminescence, assuming an exciton mechanism. The field alters the bending of the band, near the surface, and this influences both the filling of the impurity levels and the rate of surface annihilation of excitons, which can be determined by a comparison of the theory with experiment, using also results on diffusion.

V. N. Dobrovol'skiĭ (Kiev University) has a paper, "Magneto-capacity Effect in Semiconductors," in which he discusses the possibility of varying the capacity of a surface layer of space charge by applying a magnetic field parallel to the surface. Passage of a current gives rise to an excess surface charge. This effect should be more noticeable in an intrinsic semiconductor. Estimates show that in a magnetic field of 5 kOe and a reasonable electric field the capacity should change by a factor 10.

A paper by **M. Erezhepov** (Physico-technical Institute of the Ukrainian Academy), "Theory of Magnetoresistance in Semiconductors Including the Effect of Charged Impurity Centers," studies the equations for the electric conductivity and the diffusion of carriers, taking into account the screening of the Coulomb field of charged impurity centers. General expressions are obtained for the magnetoresistance in this case.

The contribution of **Z. S. Gribnikov** (Institute of Metallurgical Problems of the Ukrainian Academy), "Theory of Injection in Long Diodes," considers the distribution of non-equilibrium carriers in the presence of a current through the volume of a diode for which $d/l > 1$ (d being the length of the region and l the diffusion length). Both for an ohmic contact and for a rectifying contact the voltage rises first linearly, but afterwards it continues to grow logarithmically in the first case, and saturates in the second.

The paper by **Yu. S. Ryabinkin,** "The Influence of the Electric Field Intensity on Space Charge Limited Currents in Dielectrics and Semiconductors," investigates theoretically the voltage-current characteristics in the case in which the traps are being emptied by the electric field.

A resolution approved by the meeting noted that great attention had been given to work on electric and acoustic instabilities, thermal perturbations in quantum transport theory and the theory of phononless processes, in which new and important results had been obtained. The conference considered it worthwhile to continue and develop work in the following directions: (1) acoustic and electric instabilities, the theory of fluctuations and noise; (2) the theory of quantum generators; (3) the development of methods of many-body theory applicable to semiconductors (including problems of the electron plasma); (4) the quantum theory of transport problems; (5) the study of the energy spectra of intrinsic and impurity semiconductors; (6) the theory of the optical properties of intrinsic and impurity semiconductors and the theory of excitons; (7) the theory of resonance effects; (8) phenomena in semiconductors in strong electric fields; (9) lattice dynamics; (10) the theory of semiconductor devices.

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