Sound absorption in germanium and silicon at high temperatures

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The absorption of longitudinal and shear waves has been investigated in n- and p-type silicon and germanium with low dislocation density. The measurements were made in different crystallographic directions at frequencies 15–85 MHz in a temperature range 300–1200°K. It was discovered that the temperature dependences and the orientation dependences of the sound absorption coefficient α cannot be satisfactorily explained either by the Akhiezer phonon-phonon interaction or by the deformation electron-phonon interaction. As a consequence of the high energy of formation, direct interaction of elastic waves with thermal fluctuation defects of the latter also turns out to be ineffective. It is shown that a possible source of losses at high temperatures in the megahertz frequency range, which agrees with experiment both in order of magnitude and in its temperature and frequency dependences, can be the interaction of the ultrasonic oscillations with electrons in the conduction band and holes in the valence via thermal levels created by thermal fluctuation defects in the forbidden band.

The acoustic properties of simple semiconductors such as silicon and germanium have been studied in considerable detail (see, for example,[1]). This is connected with the fact that the technology of the growing of single crystals of these materials makes it possible to obtain samples of very high purity, with a low density of dislocations. Sound absorption in Ge and Si at low and room temperatures is chiefly associated with phonon-phonon (Akhiezer) losses. In contrast to metals, as a consequence of the low thermal conductivity, the contribution made by thermoelastic effects to the sound absorption is not amenable to experimental observation. In highly doped silicon and germanium at low temperatures, a sound absorption appears that is due to inter-valley electron relaxation, and also to the deformation potential.

However, the experimental investigations of the propagation of elastic waves in semiconductors, in spite of their extremely wide frequency range (up to 10^{10} Hz), are limited to temperatures up to 300°K. We know of only one work[2] in which ultrasonic oscillations have been excited by an electrostatic method and the sound absorption measured up to 1200°K at frequencies of 10^5 and 3×10^5 Hz in silicon and germanium. As a result of measurement on longitudinal waves along the [111] direction, two maxima in the sound absorption coefficient α have been discovered in both materials. The higher-temperature maxima of α were ascribed to the relaxation of the atoms of dissolved oxygen,[3] and the low-temperature ones to the recombination of electrons and holes, brought about by a change in the energy gap under the action of a deformation in the ultrasonic wave in accordance with the theory of the deformation potential.[4]

In the present work, we give the results of a set of high-temperature measurements in silicon and germanium for longitudinal and shear waves at frequencies 15–75 MHz. The sound absorption coefficient was measured in different crystallographic directions. The samples used for the measurements had a conductivity of n- and p-types with carried density 10^{14}–10^{17} cm^{-3}. The dislocation density in all samples did not exceed 10 cm^{-2}.

EXPERIMENT

All the measurements of the sound absorption coefficient α were conducted by the method described in[5]. Since high purity of the finish of the contacting surfaces of the samples and isolating acoustic lines is required for the high-temperature measurements according to this method, the samples were prepared in special fashion. After mechanical working, the samples were subjected to chemical polishing, which guaranteed not only high purity of the surfaces but also the removal of traces of the abrasive.

Before the measurements, the samples were annealed in a vacuum at ~1100°K for 1–2 hours, and then cooled slowly. The samples were cylinders of rather large dimensions (length 20–25 mm and diameter 25–30 mm), which significantly exceeded the ultrasonic beam cross section. The latter fact made it possible to reduce the danger of contamination of the samples from the lateral surfaces by diffusion that becomes activated at high temperatures. Thus, for the most rapidly diffusing impurity in germanium—copper—the diffusion coefficient at 1150°K does not exceed 10^{-5} cm^2/sec, meaning that after maintaining this temperature for two hours the penetration of the impurities does not exceed 2–3 mm, i.e., for a diameter of the ultrasonic beam of 10–15 mm, the impurities did not fall into the sound transmission band and did not change the properties of the sample.

Another criterion for the invariance of the properties of the samples during the measurements is the reproducibility of the results. All the experimental results carried out in the current research were obtained in repeated measurements on the same samples. We note that the acoustical and electrical properties of the samples were destroyed only by quenching, i.e., by rapid cooling from high temperatures. Under these conditions, to restore the properties, the samples were heated to 1000–1100°K, maintained at this temperature 1–2 hours, and then slowly cooled.

All the samples used in the experiments were oriented relative to the crystallographic directions with accuracy no worse than 0.5–1°.

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We emphasize that at room temperatures, in all the germanium and silicon samples, the absolute value of the sound absorption coefficient at frequencies of 15—75 MHz, both for longitudinal and shear waves, did not exceed 0.1 dB/cm, i.e., it lay within the limits of error of the measurements connected with diffraction. Therefore, although the method described in[5] allows us to measure only the increment of the sound absorption coefficient $\Delta\alpha$, actually the measurements of $\Delta\alpha$ for silicon and germanium were equivalent to the measurement of the absolute values of α. Such a small sound absorption at room temperature, as had already been noted, is associated with the fact that the principal source of loss in single crystals of germanium in the absence of dislocations are the Akhiezer phonon-phonon processes.

Figure 1 shows the temperature dependences of α for an n-type germanium sample doped with antimony, with $n_0 = 1.8 \times 10^{14}$ cm^{-3} and electrical resistivity $\rho_R = 11.2$ ohm-cm; Fig. 1a refers to the longitudinal waves and 1b to the shear waves, while the direction of propagation of the ultrasound is along [111]. It is seen from the given experimental data that the sound absorption coefficient in n-type germanium increases with increase in temperature for both longitudinal and shear waves. At temperatures close to the melting point, the temperature coefficient of α decreases. The frequency dependence turns out to be very weak but somewhat peculiar, since its form turns out to be a function of temperature. In the region of not too high temperatures (up to 800—900°K) some decrease in α with increase in frequency is observed in the frequency range 45-75 MHz. No frequency dependence was observed in the frequency range 15—45 MHz. Near the melting temperatures (1100—1500°K) the character of the $\alpha(f)$ dependence changes and α increases with increase in the frequency. No differences were observed in the behavior of $\alpha(T)$ and $\alpha(f)$ as functions of the type of wave within the accuracy of the experiment. However, it must be kept in mind that the form of the frequency dependence of α in the range of not too high temperatures can be discussed only qualitatively, inasmuch as the values of the sound absorption coefficients are rather small at these temperatures.

With the aim of clarifying the effect of the sign of the carriers on the sound absorption coefficient in a germanium sample doped with gallium (p-type), with a resistivity $\rho_R = 10$ ohm-cm at room temperature and carrier density $p_0 = 1.7 \times 10^{14}$ cm^{-3}, measurements were carried out along the [111] direction. The results indicate that the sign of the free carriers does not affect the character of the temperature and frequency dependences. However, in the range of frequencies 15—25 MHz, α in a p-type sample turns out to be somewhat smaller than the corresponding value for n-type. The difference that appears here is connected not with the temperature coefficient of α (it is experimentally constant within the limits of error) but with the fact that the growth of the sound absorption coefficient in a sample doped with gallium with increase in temperature begins at higher temperatures. At high frequencies (55—75 MHz), this difference in α is absent. The increase in the concentration of the dopant (gallium) in p-type samples leads to a decrease in the sound absorption at all frequencies, independent of the type of the wave. This is illustrated by the curves of Fig. 2, in which the results are compared of the measurements of α in samples of p-type with $p_0 = 1.7 \times 10^{14}$ cm^{-3} and $p_0 = 10^{17}$ cm^{-3} and n-type with $n_0 = 1.8 \times 10^{14}$ cm^{-3}. It is easy to see that the increase in the acceptor conentration, without changing the temperature coefficient of α, shifts the growth of the sound absorption coefficient with heating in the direction of higher temperatures.

The direction of the sound propagation has virtually no effect on the observed dependences. For example, results of measurements of α in two samples of p-type germanium with $\rho_R = 2$ ohm-cm and $p_0 = 10^{15}$ in the case of propagation of the ultrasonic oscillations along [100] and $\rho_R = 11.2$ ohm-cm and $p_0 = 1.7 \times 10^{14}$ cm^{-3} with a propagation direction along [111] are given in Fig. 3. It is seen from these that, within the limits of experimental error, the dependence of the sound absorption coefficient on the direction of propagation of sound is lacking.

The experimental results obtained in silicon are similar. With increase in temperature, α increases for all the samples studied, both for longitudinal and shear waves. However, in contrast with germanium, the frequency dependence of the sound absorption coefficient is expressed more sharply. In contrast to the usual relaxation sound absorption in silicon, α decreases with increase in frequency. It must be emphasized that, as in germanium, the increase in the frequency does not change the value of the temperature coefficient of α and only increases the temperature at which the values of the sound absorption coefficient becomes accessible to experimental measurement. However, in silicon, this temperature shift is much greater than in germanium. What has been indicated above is illustrated in Fig. 4, on which the results of measurement of α for

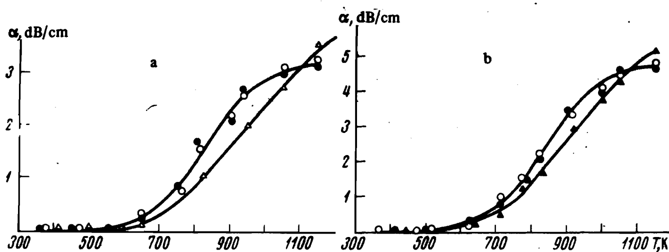

FIG. 1. Temperature dependence of the sound absorption coefficient in n-type germanium in the [111] direction: a—longitudinal waves, b—shear waves; ●—15, ○—25, ▲—55, △—85 MHz, $n_0 = 1.8 \times 10^{14}$ cm^{-3} $\rho_R = 11.2$ ohm-cm.

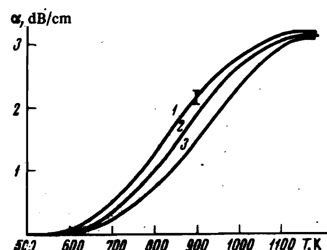

FIG. 2

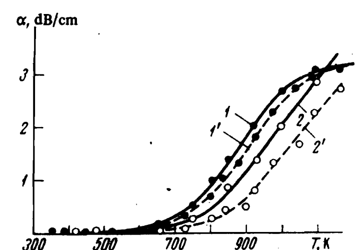

FIG. 3

FIG. 2. Temperature dependence of the sound absorption coefficient in germanium at a frequency of 15 MHz for various impurity concentrations. 1—$n_0 = 1.8 \times 10^{14}$ cm^{-3}, 2—$p_0 = 1.7 \times 10^{14}$ cm^{-3}, 3—$p_0 = 10^{17}$ cm^{-3}.

FIG. 3. Temperature dependence of the sound absorption coefficient in germanium for various directions of propagation of the oscillations: continuous curves—[111], dashed curve—[100]; 1, 1'—15 MHz, 2, 2'—85 MHz.

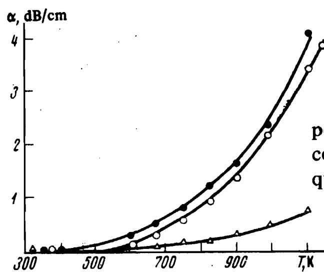

FIG. 4. Temperature dependence of the sound absorption coefficient in silicon for frequencies of 15 (●), 25 (○), 85 (△) MHz.

longitudinal waves in a sample of n-type silicon with room-temperature resistivity $\rho_R = 215$ ohm-cm are given. Increase in the amount of doping, while not changing the general temperature dependence of the sound absorption coefficient, does decrease its frequency dependence. The temperature and frequency dependences of α for shear waves are similar.

Thus the basic experimental data on the investigation of the sound absorption coefficient for longitudinal and shear waves in the megahertz range at high temperatures in silicon and germanium reduce to the following:

1) the sound absorption increases with increase in temperature;

2) the type of ultrasonic oscillations and also the direction of their propagation do not change the temperature dependence of α;

3) the sound absorption coefficient decreases in silicon with increase in frequency. The same tendency is also observed in germanium, but it is less strongly expressed; in it the frequency dependence of α is lacking in first approximation;

4) increase in the frequency does not change the temperature coefficient of α but does change the temperature at which a significant change in α with heating begins to occur;

5) the sign of the carriers, and also the concentration of the dopant, do not affect the temperature coefficient of α within the limits of accuracy of the experiment, but do change the temperature at which its significant increase begins. The effect of the dopants increases with decrease in the frequency.

DISCUSSION OF THE EXPERIMENTAL RESULTS

It is not difficult to show that the experimental data obtained cannot be satisfactorily explained within the framework of loss mechanisms describing the sound absorption in semiconductors at low and room temperatures. The phonon-phonon interaction of Akhiezer[6] in the range of frequencies $\omega\tau_{ph} \ll 1$ (τ_{ph} is the mean relaxation time of the thermal phonons) lead to a quadratic frequency dependence of the sound absorption coefficient and also, at temperatures $T > T_D$ (T_D is the Debye temperature)—to the absence of a temperature dependence of α, which is not observed in our experiments at high temperatures (for temperatures ~300°K and frequency 10^7—10^8 Hz, it was not possible to determine the frequency dependence of α reliably).

Numerical estimates of the dislocation contribution, obtained under the assumption that the bulk dislocation density is not different from the measured surface values, give a value of α that is an order of magnitude smaller than that observed experimentally. Moreover, it is impossible to attribute the frequency dependence of α in silicon to dislocations, nor the absence of a dependence of $\alpha(f)$ in germanium—the temperature dependence of the sound absorption coefficient under satisfaction of the condition $T > T_D$.[7]

Another source of energy losses of an ultrasonic wave, which is inherent in semiconductors, is the interaction of elastic waves with free carriers via the deformation potential. This mechanism of sound absorption, first considered by Weinreich,[4] arises from the fact that the deformation in an ultrasonic wave changes the width of the forbidden band in semiconductors and, consequently, the equilibrium distribution of the free carriers (in the general case of the electrons and holes). However, the change in the width of the forbidden band under the action of the deformations of the crystal is of the form

$$E_g = \varepsilon_1 u_{ii}. \tag{1}$$

Here ϵ_1 is some constant which bears the name of deformation potential, and u_{ii} is the deformation tensor in the ultrasonic wave. In other words, after a change in the equilibrium distribution of the carriers, the change in the volume in the ultrasonic wave and, consequently, the sound absorption coefficient, measured for longitudinal and shear waves, should be quite different. Moreover, according to[4], α due to deformation interaction with free carriers can be expressed in the absence of an electric field in the form

$$\alpha = -\frac{q^2 n_0 \omega}{2kTs(1+l)} \operatorname{Im} M, \tag{2}$$

$$M = \frac{1+\omega_0(1+lb)/\omega^2\tau_c(1+l)}{1+\omega_0(1+lb)/\omega^2\tau_c(1+l)+i\beta_0(1-l)\omega_0/(1+l)\omega}, \tag{3}$$

where q is the so-called acoustic charge, equal to $\epsilon_1/\rho^{1/2}s$; $l \equiv n_0/p_0$ is the ratio of concentrations of free electrons and holes, k is the Boltzmann constant, s the sound velocity, ρ the density, b the ratio of the mobilities of electrons and holes, τ_c the lifetime of the free carriers, $\omega_0 \equiv s^2/D_n$ the diffusion frequency, D_n the diffusion coefficient of the electrons, and $\beta_0 \equiv (1 + lb)/(1 - l)$. Therefore, in the range of high temperatures, the frequency dependence of α from (2) should have a relaxational character. Actually, for example, at $T = 1000°K$ we have $kT \approx 0.1$ eV, which, for ordinary doping materials (antimony, gallium), leads to the result that the lifetime of the carriers is determined not by the energy position of the impurity levels, but by the total width of the forbidden band. Therefore the typical values of the lifetimes of the carriers for these temperatures turn out to be 10^{-4}—10^{-7} sec. The diffusion frequency ω_0 is equal to 10^{10}—10^{11} Hz in order of magnitude for germanium and silicon. Consequently, for the megahertz range ($\omega \lesssim 10^8$ Hz)

$$\alpha \approx \frac{q^2 n_0}{2kTs(1+l)} \frac{\omega^2\tau_c}{1+\omega^2\tau_c^2}. \tag{3a}$$

It is easy to see that the $\alpha(\omega)$ dependence from (3a) contradicts the experimental results. We emphasize that the experiments in[2], on the basis of which the hypothesis of the deformation (according to Weinreich) origin of the maximum of the sound absorption coefficients in silicon and germanium at high temperatures was introduced, have been performed only for longitudinal waves in a narrow frequency interval.

The experimental results obtained in silicon and germanium cannot be satisfactorily explained by the mechanism of interaction of ultrasonic oscillations with

point defects, which play an important role in sound absorption in metals at high temperatures in the megahertz frequency range.[7]

Numerical estimates of the sound absorption coefficient, due to the redistribution of point defects,[1] show that even in the range $\omega\tau = 1$ α turns out to be of the order of units of dB/cm for impurity concentrations $\approx 10^{-5}$, i.e., electrically active impurities doping the semiconductors, cannot make a significant contribution to the experimentally measured sound absorption. The concentrations of the electrically inactive impurities such as oxygen, is added to the measurement much worse. Therefore, the value of α which is connected with such a form of impurities, can be assumed to be very approximate. In this case, a comparison with experiment encounters significant difficulties. However, the sound absorption connected with nonthermal point defects is strongly anisotropic.[1] Therefore, within the framework of such a mechanism of interaction, it is not possible to explain why the measurements results are identical for directions of propagation of the ultrasonic oscillations along [111] and [100], regardless of the type of wave, while for both crystalline lattices of silicon and germanium, these directions are significantly different.

We note that the conclusions that there is no significant contribution from impurity atoms of oxygen to the sound absorption measured by us do not contradict the results of[2], since the higher temperature maxima of α discovered there for longitudinal waves in the [111] direction are observed at temperatures close to the melting temperature of the samples, at a frequency of 10^5 Hz. Increase of the frequency by two or three orders of magnitude should shift the maxima of α to the range of temperatures that exceed the melting temperature.

Another mechanism characteristic of metals at high temperatures is the interaction of the elastic waves with thermal point defects through modulation of the probabilities of their creation and annihilation, and the corresponding contribution to the free energy of the crystal[7] also gives small values of the sound absorption coefficient for silicon and germanium, as a consequence of the low concentration of thermal fluctuation defects. Thermal point defects in germanium and silicon have been studied in sufficient detail by various methods[8] and are characterized by formation energies of the order of 2–3 eV. As a rule, they represent vacancies and interstitial atoms. As a result, the concentration of such defects even for temperatures of 1000–1100°K does not exceed 10^{-6}–10^{-8}, which, under optimal relaxation conditions gives a value of α no greater than 10^{-2} dB/cm, which is two orders smaller than the values observed experimentally. However, in the calculation of the sound absorption coefficient associated with the point defects in semiconductors, in contrast with metals, it is probably necessary to recognize that the thermal defects in silicon and germanium can change the equilibrium concentration of the free charge carriers. It is known that the thermal defects in semiconductors, distorting the initial crystalline lattice, create additional local energy levels in the forbidden band, both of the acceptor (for example, in germanium) and donor (for example in silicon) types. As a result, at high temperatures, the change in the concentration of free carriers with heating occurs not only because of direct transitions from the valence band to the conduction band, but also because of the appearance of additional thermal levels. These effects under definite conditions can lead also to a change in the sign of the carriers—the so-called thermal conversion.[8] Therefore, the ultrasonic oscillations, modulating the equilibrium concentration of thermal defects, change the equilibrium concentration of the free charge carriers, which can lead to additional sound absorption.

If the time of establishment of the equilibrium distribution in the conduction band is neglected, a change in the concentration of the free carriers, and also in the concentration of ionized atoms, follows after a change in the concentration of thermal fluctuation defects. This concentration change is connected with the appearance of additional components in the free energy of the crystal, which also leads to a relaxational sound absorption. However, the sound absorption coefficient due to this mechanism turns out to be small in silicon and germanium. This is a consequence of the low concentration of the point defects, since, regardless of the depth of the energy level created by the point defects in the forbidden band, the dependence of the chemical potential on the concentration of free carriers that are excited in the conduction band (in the valence band) because of the thermal levels can be represented in the form that is usual for an impurity semiconductor, namely $\ln Ac$ (c is identical with the concentration of point defects, if all the thermal levels are ionized, A is a weak function of the temperature, in the first approximation, independent of the deformation and concentration of the carriers), and α is determined by the derivatives of the chemical potential.

The situation changes significantly when account is taken of the fact that the establishment of an equilibrium distribution of free electrons and holes requires a finite time. In this sense, the mechanism considered is equivalent to sound absorption due to the deformation potential. However, the essential difference is that if perturbation of the equilibrium distribution of free charge carriers in the theory of[4] takes place as a consequence of the change in the width of the forbidden band, then, in the given approach, the interaction of elastic oscillations with free charge carriers occurs through modulation of the concentration of the "impurity" levels in the forbidden band. The equilibrium quantity of additional levels in the forbidden band is, in the general case, proportional to the number of point defects in the crystal. Since the point thermal defects in silicon and germanium create shallow levels,[8] it can be assumed in the high temperature range that they are completely ionized and that the change in the quantity of free electrons and holes is determined by the change in the quantity of thermal levels under the action of deformations in the ultrasonic wave.

In such an approach, we can explain the basic experimental facts that are not describable by the theory of the deformation potential. First, the interaction of the ultrasonic oscillations with the free charge carriers proceeds via point defects both for longitudinal and shear waves, for any direction of propagation of the ultrasound. Second, within the framework of such an interaction, we can explain, at least qualitatively, the specific frequency dependence of α by account of the time τ_0 necessary for the formation of the thermal level: if $1/\omega \gg \tau_0$, then the number of thermal levels additionally due to the deformation practically coincides with the number of point defects; in the opposite

limiting case, the change in the concentration of thermal point defects will not lead to any change in the concentration of thermal levels in the forbidden band, and consequently, to sound absorption.

Numerical estimates of α due to electron-phonon interaction through thermal fluctuation defects can be carried out in the following fashion. Neglecting the temperature change δT for propagation of ultrasonic oscillations ($\delta T = 0$ for shear waves in the isotropic approximation, but we are interested in interactions which make a contribution to the sound absorption for both types of waves), the equilibrium number N^e of point defects of a definite sort in the deformed crystal is equal to[9]

$$N^e = N_0(T) \exp\left(\frac{K\Omega_{ik}u_{ik}}{kT}\right). \quad (4)$$

Here $N_0(T)$ is the equilibrium number of point defects in the undeformed crystal, and $K\Omega_{ik}u_{ik}$ characterizes the energy of interaction of the point defect with the field of elastic deformations in an approximation that is linear in the deformation, K is the isothermal elastic modulus, and Ω_{ik} is the symmetric tensor which characterizes the deformation of the lattice due to the appearance of a single thermal fluctuation defect. Therefore, the instantaneous change in the number of thermal point defects N under the action of the ultrasonic wave takes the form[7]

$$\delta N = \frac{\delta N^e}{1+i\omega\tau_{td}} = \frac{N_0(T) K\Omega_{ik}u_{ik}}{kT(1+i\omega\tau_{td})}, \quad (5)$$

where τ_{td} is the relaxation time, which is determined by the probability of annihilation of the thermal fluctuation defects in unit time.

For simplicity, we assume that there are thermal fluctuation defects of only one type in the crystal and each defect creates a thermal level in the forbidden band. As a consequence of the small depth (as a rule, less than 0.1 eV), at high temperatures the thermal levels are practically completely ionized. Consequently, without account of diffusion, recombination and trapping of the free carriers, the change in the amount of electrons in the band, δn_∞^T, is proportional to δN. In what follows, we shall assume for definiteness that the thermal defects create shallow singly-ionized acceptor levels and, correspondingly, direct interaction of the sound with the carriers through the thermal fluctuation defects exists only with holes in the valence band. The conduction electrons interact with the ultrasonic oscillations only because of the disruption of equilibrium distribution of the holes. This case is more completely realized for germanium, in which the point defects are interpreted basically as monovacancies that create acceptor levels in the forbidden band. The thermal defects in silicon are regarded as being vacancy + impurity complexes and create donor levels.[8]

The tensor Ω_{ik}, being a symmetric tensor of second rank, can be reduced to three mutually perpendicular principal axes. In this system of coordinates,

$$\delta p_\infty^T = \delta N = \frac{N_0(T) K\Omega_m u_{mn}}{kT(1+i\omega\tau_{td})}. \quad (6)$$

Here u_{mn} are the diagonal components of the deformation tensor in the wave, reduced to the principal axes of the tensor Ω_{ik}, m = n. It is easy to see that the quantity $K\Omega_{nm}$ plays the role of the deformation potential; however, it turns out to be different for each component u_{mm}. Following[4], we introduce the Hamiltonian of a unit volume

$$H = \frac{1}{2}\rho\left(\frac{\partial\varkappa}{\partial t}\right)^2 + \frac{1}{2}\rho s^2(\nabla\varkappa)^2 + U_{int}, \quad (7)$$

where κ is the displacement in the wave and U_{int} is the energy of interaction of sound with the carriers through the thermal fluctuation defect. In accord with (6),

$$U_{int} = p\frac{K\Omega_m u_{mn}}{1+i\omega\tau_{td}}; \quad m=n. \quad (8)$$

We emphasize that the concentration of holes p, which interact with the ultrasonic wave, is not identical with the total concentration of holes in the valence band.

One can obtain from (7), with account of (8), a wave equation that describes the propagation of the ultrasonic wave in the medium with the interaction:

$$\nabla^2\varkappa - \frac{1}{s^2}\frac{\partial^2\varkappa}{\partial t^2} = \frac{1}{\rho s^2}\frac{K\Omega_m \partial p/\partial x_m}{1+i\omega\tau_{td}}\mathbf{1}_m, \quad (9)$$

where $\mathbf{1}_m$ are unit vectors of the principal axes of the tensor Ω_{ik}. For $\omega\tau_{td} \ll 1$ and $\Omega_m = \Omega_0$, the wave equation (9) transforms into the wave equation from[4], in which the deformation interaction is included in the form (1).

Thus the interaction of sound with carriers through the modulation of the probability of formation of thermal levels in the forbidden band can be described in terms of the specific deformation potential. However, differences in principle do exist between the electron-phonon interactions arising from the deformation potential and from thermal fluctuation defects. First, by means of the deformation potential, the ultrasonic wave interacts with all the electrons in the conduction band and holes in the valence band, while in the case considered, the interaction takes place only on the part of carriers, for example, holes in the valence band, that are due to thermal levels in the forbidden band. This leads, on the one hand, to a strong temperature dependence of δp_∞^T in (6) and on the other to the result that the interaction through the thermal fluctuation defects appears only for sufficiently high temperatures. Equilibrium concentration of electrons interacting with the ultrasonic wave in the conduction band for the considered case can be found from the following considerations. Let n_{00} and p_{00} be respectively the concentration of electrons in the conduction band and holes in the valence band in the absence of thermal levels. As is well known, they can be expressed in terms of the density of states N_c in the conduction band and the width of the forbidden band E_g:

$$n_{00}p_{00} = N_c \exp(-E_g/kT) = n_i^2.$$

If $N_0(T)$ singly ionized acceptor levels are formed in the crystal, then

$$(n_{00}-n_0^T)(p_{00}+p_0^T) = n_i^2; \quad p_0^T = N_0(T), \quad (10a)$$

whence

$$n_0^T = \frac{n_{00}N_0(T)}{p_{00}+N_0(T)}. \quad (10b)$$

Another feature of this type of interaction is associated with the fact that, according to (5), it is realized both for longitudinal and for shear waves. Thus, if, according to Weinreich[4], δp_∞ is identical in phase and deformation in the wave, then, in the interaction through the thermal fluctuation defect, they are shifted in phase (see (6)).

The conditions $\omega/\omega_c \ll 1/\omega_c$ is the frequency of dielectric relaxation) and $s\omega \gg r_D$ (r_D is the Debye screening radius) are satisfied at frequencies 10^7-10^8 Hz in silicon and germanium by a large margin. Hence the equation for the current and the equation of continuity can be written as in[4]. Correspondingly the sound absorption coefficient, due to the thermal fluctuation defects, turns out to be similar to (2):

$$\alpha = -\frac{(K\Omega_m)^2 n_0^T \omega}{2kT\rho s^3(1+l)} \operatorname{Im}\frac{M}{1+i\omega\tau_{td}} = \frac{(K\Omega_m)^2 n_0^T \omega}{2kT\rho s^3(1+l)}$$

$$\times\left\{\frac{\omega\tau_{td}}{1+\omega^2\tau_{td}^2}\frac{[1+\omega_0(1+lb)/\omega^2\tau_c(1+l)]^2}{[1+\omega_0(1+lb)/\omega^2\tau_c(1+l)]^2+\beta_0^2\omega_0^2(1-l)^2/\omega^2(1+l)^2}\right. \tag{11}$$

$$\left.+\frac{1}{1+\omega^2\tau_{td}^2}\frac{[\beta_0(1-l)\omega_0/(1+l)\omega][1+\omega_0(1+lb)/\omega^2\tau_c(1+l)]}{[1+\omega_0(1+lb)/\omega^2\tau_c(1+l)]^2+\beta_0^2\omega_0^2(1-l)^2/\omega^2(1+l)^2}\right\}.$$

Here s is the sound velocity for the corresponding direction of propagation and wavetype, $l \equiv n_0^T/p_0^T$, and n_0^T and p_0^T are determined by Eqs. (10).

In the range of frequencies 10^7-10^8 Hz of interest to us, (11) is significantly simplified, since $\omega \ll \omega_0$ (for germanium and silicon, $10^{10}-10^{11}$ Hz), $\omega\tau_t \gg 1$ and $\omega\tau_{td} > 1$. Therefore,

$$\alpha \approx \frac{(K\Omega_m)^2 n_0^T \omega^2 \tau_{td}}{2kT\rho s^3(1+l)(1+\omega^2\tau_{td}^2)}. \tag{12}$$

In the range of lower temperatures $n_0T/(1+l) \sim N_0(T) \to 0$, and $\omega\tau_{td} \gg 1$, and, consequently, $\alpha \to 0$. With increase in the temperature α increases as a consequence of the increase in the concentration of point defects and decrease in τ_{td}. For temperatures $\sim 1000°$K, we can take for estimates the typical values for germanium of $\tau \approx 10^{-7}$ sec, $N_0(T) \approx 10^{17}$ cm^{-3}, and α turns out to be of the order of units of dB/cm (for the calculations, it was assumed that $\Omega_m \sim a^3$, where a is the lattice constant), which is identical in order of magnitude with the experimental values of α. Moreover, practically all the basic experimental results can be interpreted within the framework of the interaction of elastic waves with carriers through the thermal fluctuation defects.

1. Since $n_0^T/(1+l) \approx N_0(T)$ in the range of high temperatures, then the temperature dependence of the sound absorption coefficient is determined by the factor $N_0(T)\tau_{td}/(1+\omega^2\tau_{td}^2)$. Inasmuch as

$$\dot{N}(T) = A_{cr}(N^* - N) - A_{an}N, \tag{13}$$

where A_{cr} and A_{an} are the probabilities of creation and annihilation of thermal fluctuation point defects in unit time, N^* is Avogadro's number, it follows that

$$N_0(T) = A_{cr}/A_{an}, \quad \tau_{td} = 1/A_{an} \tag{14}$$

and at $\omega\tau_{td} > 1$ the temperature coefficient α depends only on the probability of creation of thermal fluctuation defects, and increases with temperature as $\exp(-\varphi/kT)$ (φ is the value of the potential barrier, with the surmounting of which is connected the formation of the thermal fluctuation defect). Estimates of φ from experimental data give ~ 1 eV, which is quite reasonable.

2. The orientational dependence of α is determined by the shape of the characteristic surface of the tensor Ω_{ik} which, for simple lattices, is probably close to spherical.

3. Doping of the crystal at not too high temperatures decreases the value of the sound absorption coefficient, without changing its temperature coefficient (see (10)); in the region of natural conductivity (high temperatures) the effect of doping decreases.

The experimental results obtained in[2] can also be explained within the context of such an approach, since the low-temperature relaxation maxima discovered by the author (in germanium at $T = 670°$K) at a frequency of 10^5 Hz lead to $\tau_{td} \approx 10^{-5}$ sec, which agrees well with the estimates for the lifetime of the thermal fluctuation defects at these temperatures. Moreover, the argument of the exponential in τ_{td}, determined from the condition of relaxation ($\omega\tau_{td} = 1$) in[2], also turned out to be ≈ 1 eV, but was connected with the width of the forbidden band. It is very important that the considered mechanism allow us to give an interpretation of the specific frequency dependence of the sound absorption coefficient in silicon and the reason for its difference from $\alpha(\omega)$ in germanium.

We have assumed above that all the excess thermal fluctuation defects, formed under the action of the deformations in the ultrasonic wave, create additional energy levels in the forbidden band, which is equivalent to the assumption that the period T_s of the sound wave exceeds the time τ_0 necessary for the creation of such a thermal level. In the absence of the sound wave, the kinetics of formation of the thermal levels can be represented in the form ($N_0(T) \ll N^*$)

$$\dot{n}_0^T = -A_{an}^0 n_0^T + A_{cr}^0 \xi(1/A_{an}^0, \tau_0) N^*. \tag{15}$$

Here $\xi(1/A_{an}^0, \tau_0)$ determines the probability of formation of the thermal level within the lifetime of the thermal fluctuation defect $1/A_{an}^0$. The deformation in the ultrasonic wave, modulating the probabilities of creation and annihilation of the thermal fluctuation defects, changes the equilibrium concentration of thermal defects, which, for $T_s > 1/A_{an}^0 > \tau_0$, leads to the purely relaxational sound absorption considered above. It is evident that for $1/A_{an}^0 < \tau_0$ the equilibrium concentration of thermal levels is not equal to the equilibrium concentration of point defects, but is determined by the specific kinetics of level formation. However, for $T > 1/A_{an}^0$, the process of establishment of equilibrium remains relaxational. For $T < 1/A_{an}^0$, the situation changes. Upon neglect of the dependence $\tau_0(u_{ik})$ and also of the change of ξ for change in the lifetime of the thermal fluctuation defects, we have

$$\dot{n}^T = -(A_{an}^0 + \delta A_{an}) n^T + A_{cr}^0 \xi(1/A_{an}^0, \tau_0) N^* + \delta A_{cr} \xi(T_s, \tau_0) N^*, \tag{16}$$

whence, if $n^T = n_0^T + \delta n^T$ and $\delta n^T \sim e^{i\omega t}$, then

$$\delta\dot{n}^T \approx -A_{an}^0 \delta n^T - n_0^T \delta A_{an} + \delta A_{cr} \xi(T_s, \tau_0) N^*. \tag{17}$$

In the deformed crystal, the probabilities of creation and annihilation per unit time of the thermal fluctuation defects can be written as

$$A_{cr}^e = \nu \exp[(\varphi + aK\Omega_{ik}u_{ik})/kT], \quad A_{an}^e = \nu' \exp[(\varphi' - bK\Omega_{ik}u_{ik})/kT],$$

where $a + b = 1$ (see (4) and (13)). Therefore,

$$\delta n^T = \frac{[a n_0^T + b N_0 \xi(T_s, \tau_0)] K\Omega_{ik} u_{ik}}{1 + i\omega\tau_{td}}. \tag{18}$$

Consideration of the specific kinetics of formation of thermal levels in the forbidden band of a semiconductor lies outside the framework of the present research; however, several qualitative conclusions can be drawn on the basis of (18).

In germanium, as has been pointed out previously, monovacancies serve as sources of thermal acceptor

levels.[8] Consequently, the probability of formation of a thermal acceptor level under the conditions of the formation of monovacancies and the distortion of the initial crystalline lattice is determined by the probability of capture of the electron from the valence band. In this case, τ_0 is small and corresponding, $\xi(1/A^0_{an}, \tau_0) = \xi(T_S, \tau_0) = 1$, which leads to the usual frequency dependence $\alpha(\omega)$. If a certain decrease of α at high frequencies, observed in germanium in our experiments, is applied to this process, then we can get for τ_0 values $\approx 10^{-9}$ sec.

In contrast with germanium, the formation of thermal donor levels in silicon is connected with the creation of the impurity + vacancy complex;[8] for otherwise equal conditions, this strongly increases τ_0 because of the low concentration (right up to very high temperatures) of the impurities and thermal fluctuation defects. If it is assumed that the formation of the impurity-vacancy complex takes place at the expense of diffusion, we can then make the following estimates for τ_0: $\tau_0 \approx r^2/2D$, $r \approx N_0^{-1/2}$. Taking $N_0 \approx 10^{16}\ cm^{-3}$ and for a diffusion coefficient $D = 10^{-6}\ cm^2/sec$, we get for τ_0 values 10^{-6}—10^{-7} sec. In the range of relatively low temperatures, the values of τ_0 will be still larger. Thus, for frequencies 10^7—10^8 Hz, $\xi(T_S, \tau_0)$ turns out to be a decaying function of the frequency, which was also noted in the experiments on silicon.

It is evident that the explicit form of the frequency dependence is determined by the specific diffusion mechanism. Since the diffusion coefficient of thermal fluctuation defects in semiconductors is much less than for impurities, up to temperatures close to the melting point, it follows that in first approximation we can assume that the formation of complexes in silicon is connected with the diffusion of impurities in the case of immobile thermal defects. If we write down the diffusion of the impurities in terms of one-dimensional uncorrelated random discontinuities, then, as is well known,[10] the probability for the diffusing particle $W(r, t)$ turns out to be equal to

$$W(r,t) \propto {}^1/_2(\pi Dt)^{-1/2} \exp(-r^2/4Dt). \tag{19}$$

at the instant of time t at some point at a distance r from the initial position. Identifying $\xi(T_S, r_0)$ with the probability for the diffusing particles to fall in the region $r_0 + \Delta$ at any instant of time $t \le T_S$, we have

$$\xi(T_s, r_0) \propto \frac{1}{T_s}\int_0^{T_s} W(r_0,t)\,dt = \frac{1}{2}(\pi D\tau_0^{1/2}T_s^{1/2})^{-1/2}\exp\left(-\frac{\tau_0}{2T_s}\right)M_{-3/4,\,1/4}\left(\frac{\tau_0}{T_s}\right)$$

Here M_{mn} are the Whittaker functions, $\tau_0 \equiv r_0^2/4D$. In the general case, analysis of the dependence of $\xi(T_S, r_0)$ is rather complicated; however, for large τ_0,[11]

$$M_{-3/4,\,1/4} \approx \exp\left(-\frac{\tau_0}{2T_s}\right)\left(\frac{\tau_0}{T_s}\right)^{-3/4}.$$

Consequently,

$$\xi(T_s, r_0) \propto (\pi D\tau_0^2)^{-1/2}T_s^{1/4}\exp\left(-\frac{\tau_0}{T_s}\right). \tag{20}$$

The results of our experiments on the measurement of the sound absorption coefficient in silicon (Fig. 4) at various frequencies are well approximated by an exponential frequency dependence. Since τ_0 is a strong function of the temperature, then, the dependence $\alpha(\omega)$ changes with increase in temperature, which has also been noted experimentally. It is obvious that account of the interaction between the impurities and the thermal fluctuation defects, and the correspondingly directed drift of impurities, distorts the frequency dependence of α, although in this case the character of the frequency dependence remains exponential.

Thus, the basic experimental results on the sound absorption in silicon and germanium in the frequency range 10^5—10^8 Hz can be explained by the interaction of elastic oscillations with the charge carriers through ultrasonic modulation of the probabilities of creation and annihilation of the thermal fluctuation defects, both in order of magnitude and in the frequency and orientation dependences.

In conclusion, we note that in semiconductors at high temperatures, observation and amplification of sound is possible, connected with the interaction with the carriers through the thermal fluctuation defects. Account of the drawing constant electric field can be carried out by the usual method[4] and leads to the replacement of β_0 in (11) by the quantity $(\beta_0 - \beta^E)\beta^E$ is the ratio of the drift velocity of the carriers to the sound velocity). Here it is necessary to take it into account that sound amplification can take place only at the expense of the second component in (11). Therefore, although $K\Omega_m > \epsilon_1$ as a rule, for observation of the significant values of the sound amplification coefficient, it is necessary that $\omega\tau_{td} < 1$. This condition increases the sound amplification both at the expense of growth of the second component in (11) and at the expense of a decrease in the effect of the first component, which does not change in first approximation in the application of a constant external field. Therefore, the maximum amplification of the sound should be observed at temperatures that are close to the melting point of the crystal, where the condition $\omega\tau_{td} \ll 1$ can be realized at sufficiently high frequencies.

[1] Physical Acoustics, v. IIIB (W.P. Mason, ed.) Academic Press, N. Y., 1965.
[2] P. D. Southgate, Proc. Phys. Soc. (London) 76, 385 (1960).
[3] C. Haas, Phys. Chem. Solids, 15, 108 (1960).
[4] G. Weinreich, Phys. Rev. 104, 321 (1956).
[5] M. B. Gitis and A. G. Kopanskiĭ, Akust, Zh. 18, 381 (1972) [Sov. Phys.-Acoustics 18, 320 (1973)].
[6] A. I. Akhiezer, Zh. Eksp. Teor. Fiz. 9, 1318 (1938).
[7] M. B. Gitis, Zh. Eksp. Teor. Fiz. 67, 363 (1974) [Sov. Phys.-JETP 40,181 (1974)].
[8] B. I. Boltaks, Diffuziya i tochechnye defekty v poly-provodnikahk (Diffusion and Point Defects in Semiconductors) Nauka, 1972.
[9] A. M. Kosevich, Osnovy mekhaniki kristallicheskoĭ reshetki (Fundamentals of the Mechanics of the Crystalline Lattice) Nauka, 1972.
[10] J. Manning, Kinetics of the Diffusion of Atoms in Crystals (Russian Translation), Mir, 1971).
[11] I. S. Gradshteĭn and I. M. Ryzhik, Tablitsy integralov, summ, ryadov i proizvedeniĭ (Tables of Integrals, Sums, Series and Products), Nauka, 1971.

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