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# INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

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# THEORY OF THE AUGER EFFECT IN AN INTENSE ACOUSTIC NOISE FIELD[1]

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ABSTRACT

A study is given of the effect on Auger processes produced by an intense acoustic noise flux affecting charge carriers via deformation-potential interaction. The calculation of Auger coefficients is carried out within a semiclassical approach to the acoustic noise field and non-degenerate carrier statistics. Simple analytic expressions are then obtained, which expose an exponential dependence of the Auger coefficients on flux intensity. The Auger recombination is found, in analogy with the case of piezoelectric noise field, to be strongly enhanced as compared to that in no-noise conditions by up to several orders of magnitude at high flux intensity, short acoustic wavelength, small carrier concentration and low temperature.

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## §1. Introduction

More than 30 years ago, Landsberg and Beattie published their work on Auger recombination in semiconductors,[1,2] which was the beginning of many theoretical and experimental investigations of this non-radiative process. Nevertheless, it should be noted that most of them were concerned with crystalline semiconductors characterized by translation symmetry.[3–5]

Recently, some attention has been drawn to non-radiative processes in disordered semiconductors featured by the lack of translation symmetry.[6–16] The theoretical studies of Takeshima and Quang have shown that the disorder caused by some random field existing in a sample may give rise to a remarkable enhancement of Auger transition.

It is well known[17,18] that acoustic noise in a medium can be amplified when the drift velocity of free carriers due to an applied dc electric field exceeds the velocity of sound. Then, the charge carriers in the sample are generally affected strongly by the acoustic waves over deformation-potential interaction and, in some particular materials, also via piezoelectric interaction. Obviously, the force fields associated with an acoustic noise assume randomness in nature. Consequently, the charge carriers in a semiconductor travelled by an intense acoustic noise flux form, in essence, a non-crystalline system whose disorder is brought about by random fields.

It was pointed out[19,20] that by virtue of the random field-induced disorder the electronic energy spectrum of a semiconductor is considerably changed, e.g. there exist density-of-state tails deep in its band gap. This modification of the electronic band structure implies, in turn, relevant changes in observable properties of the sample, especially in the optical properties related to radiative transitions. Thus, the noise fields are also thought to exert a significant influence on non-radiative processes. Indeed, owing to the piezoelectric field accompanying an acoustic noise the band edges of the conduction and valence bands are seen to be equally bent, the band gap still remaining as constant all over the sample. Then, it was indicated theoreticaly[14] that the random piezoelectric field is able to enhance drastically Auger recombination in an acoustoelectric domain. Contrary to the case of piezoelectric coupling, the band edges of the conduction and valence bands are, in general, bent differently because of deformation-potential interaction. The result is that the band gap is to fluctuate chaotically along the sample.

It is the aim of the present paper to study the effect of the band-gap fluctuations due to deformation-potential coupling on band-band Auger processes occurring in semiconductors through which an intense acoustic noise flux propagates. This problem is of some practical interest in view of offering a possibility to estimate a characteristic of the acoustic noise flux (its intensity) directly from Auger lifetime measurements. In §2 below, we gather the formulae to be used for calculating the Auger coefficients for non-degenerate carriers moving in a random field. The random deformation-potential energy of the charge carriers produced by an acoustic noise flux is treated in detail in §3. Evaluation of the influence of the band gap fluctuations on various Auger processes proceeds in §4, where plots and conclusions are contained.

## §2. Basic Formulation

To start with, we present the assumptions and equations that form a basis for analysing the effect of an acoustic noise field on Auger recombination in semiconductors.

It is well known[19,20] that in plenty of systems of physical interest the disorder is normally caused by some random field. In general, the field acts differently on the electrons in the conduction band and the holes in the valence band so that the random potential energy of the charge carriers depends on the band index, $U_l(\boldsymbol{R})$, and hence the band gap *fluctuates chaotically along the sample.*

In what follows, we will restrict the discussion to the case where $U_l(\boldsymbol{R})$ is a Gaussian



field so that it may be adequately described by the binary correlation function:[19,20]

$$\Psi_{ll'}(\boldsymbol{R},\boldsymbol{R}') = \langle U_l(\boldsymbol{R})U_{l'}(\boldsymbol{R}')\rangle. \tag{1}$$

Here the angular brackets indicate averaging over all configurations of the random field, the band indices $l = C,\ V$ refer to the conduction and valence bands, respectively.

Furthermore, the field in question is assumed to obey the following inequality:

$$\frac{\hbar^2\psi_{2l}}{4m_l\psi_{1l}^{3/2}} \ll 1, \quad (l = C,\ V), \tag{2}$$

where $m_l$ denotes the effective mass of the $l$-th band, $\psi_{1l}$ and $2\psi_{2l}$ are the mean squares of the random potential fluctuations and the field strength, respectively:

$$\psi_{1l} = \Psi_{ll}(\boldsymbol{R},\boldsymbol{R}) = \langle U_l^2\rangle \tag{3}$$

and

$$\psi_{2l} = \frac{1}{2}\nabla_R\nabla_{R'}\Psi_{ll}(\boldsymbol{R},\boldsymbol{R}')\,|_{R=R'} = \frac{1}{2}\langle(\nabla U_l)^2\rangle. \tag{4}$$

It has been shown[19,20] that if the inequality (2) is fulfilled the field $U_l(\boldsymbol{R})$ varies slowly on the average in space so that a semiclassical approach to it may be applicable. As a consequence, in the purely classical approximation we may arrive at an interesting representation of the Auger coefficient for a recombination process of non-equilibrium carriers moving in a random field:[12]

$$C = \exp\left(\frac{\psi_s}{2T^2}\right)\int_{-\infty}^{\infty} dU P(U) C_0(E_g - \psi_{sg}/T - U). \tag{5}$$

Here $C_0$ means the Auger coefficient of the sample in no-field conditions, but now with the band gap shifted as $E_g - \psi_{sg}/T - U$, $E_g$ and $T$ being the band gap and the thermal energy of the sample, respectively; $P(U)$ is the distribution function of the band gap fluctuations:

$$P(U) = \frac{1}{\sqrt{2\pi\psi_g}}\exp\left(-\frac{U^2}{2\psi_g}\right). \tag{6}$$

The $\psi_s$, $\psi_{sg}$ and $\psi_g$ stand for random parameters which are given only in terms of $\psi_{1l}$ ($l = C,\ V$).[12]

In derivation of eq. (5), the root mean square of the band gap fluctuations is supposed to be small as compared to the band gap of the sample:

$$\sqrt{\psi_g} \ll E_g, \qquad (7)$$

which allows neglecting interband scattering owing to the field. Moreover, the electrons in the conduction band and the holes in the valence band are assumed to make up non-degenerate gases. A condition for Boltzmann statistics to be valid reads as:[12,21]

$$\psi_{sg}/T \ll E_g. \qquad (8)$$

It is worthy to remark that although the Auger coefficients of a sample in the presence and in the absence of a random field are well known to depend on the band structure of the material in question, their ratio proves to exhibit a weak band-structure dependence. Indeed, for a Gaussian distribution described by eq. (6) we have on the order of magnitude:

$$U \sim \sqrt{\psi_g}. \qquad (9)$$

Then, under the inequalities (7), (8) we have approximately:

$$C_0(E_g - \psi_{sg}/T - U) \sim C_0(E_g) \equiv C_0. \qquad (10)$$

Therefore, eq. (5) yields the following estimation:

$$\frac{C}{C_0} \sim \exp\left(\frac{\psi_s}{2T^2}\right). \qquad (11)$$

It is suggested from the right hand side of eq. (11) that the ratio of the Auger coefficients seems to depend only weakly on the band structure.

The ratio $C/C_0$ can be clearly considered as a measure of the effect of a random field on Auger processes. Since the aim of the present paper is to examine the random-field influence, i.e. to evaluate the Auger coefficient ratio, we may hereafter assume parabolic energy bands with effective masses $m_C$, $m_H$ and $m_S$ for the conduction, heavy hole and split-off bands, respectively.



In addition, we suppose that albeit the band edges of the conduction and valence bands may be ununiformly bent, the ratio

$$\gamma = \frac{U_V(\boldsymbol{R})}{U_C(\boldsymbol{R})} \qquad (12)$$

is non-random and independent of space coordinate $\boldsymbol{R}$. As seen later, this is the case when the random field has a deformation potential-like origin [see eq.(21)].

Then eqs. (5), (6) in combination with these assumptions may lead to a simple expression given below for the ratio between the Auger coefficients $C_i$ and $C_{i0}$ for a sample with and without a random field:[12]

$$\frac{C_i}{C_{i0}} = \exp\left(\frac{\psi_i^{AC}}{2T^2}\right), \quad (i = e,\ h), \qquad (13)$$

where

$$\psi_i^{AC} = \alpha_i^2 \psi_{1C}, \qquad (14)$$

with $\psi_{1C}$ being the mean square potential fluctuation relative to the conduction band. In what follows, the subscript $i = e$ or $h$ denotes the conduction band or valence band process, and the suffix 0 means, as before, the absence of the disorder. The disorder effect is found generally to depend on the process kind under consideration. It holds for the conduction band process due to electron-electron collision, e.g. the CHCC process sketched in Fig. 1:

$$\alpha_e = 2 - \gamma + \frac{m_C}{m_C + m_H}(1 - \gamma), \qquad (15)$$

and for the valence band process owing to hole-hole collision, e.g. the CHSH process depicted in Fig. 2:

$$\alpha_h = 1 - 2\gamma + \frac{m_S}{m_C + 2m_H - m_S}(1 - \gamma). \qquad (16)$$

Eqs. (13) to (16) establish our starting point for discussion of the influence of band gap fluctuations given rise to by an acoustic noise field on the Auger processes in question. From these equations it is easily seen that if the band edges of the conduction and valence bands are uniformly bent, the band gap remaining unchanged over the whole sample, we have $\gamma = 1$, hence $\alpha_i^2 = 1$ and $\psi_i^{AC} = \psi_{IC}$, ($i = e$, $h$). This means that in the present case the disorder influence becomes independent of the process kind. Such a situation is met with the random field created by ionized impurities spaced chaotically in a heavily doped sample[13] or the piezoelectric noise field.[14]

An examination of eqs. (13) to (16) shows that the Auger transition may be strongly enhanced by an exponential function of the random parameter $\psi_{IC}$ whose exponent depends on the non- random parameter $\gamma$ and the effective masses of the material as well. It is, however, to be noticed that for III-V compounds the effective mass ratios entering eqs. (15), (16) are far smaller than unity so that the disorder effect turns out, in fact, to depend merely weakly on the band structure of the sample in accordance with the foregoing statement.

To end this section, it is to be recalled that in the purely classical approximation with respect to the random field, adopted in the present paper, the overlap integrals as well as the momentum-conserving $\delta$-function still remain unaffected. This is a consequence of the fact that all forces relative to derivatives of the random potential were neglected, only the potential is retained. The situation could be altered when taking of the quantum corrections as indicated previously.[15]

## §3. Acoustic Noise Field Associated with Deformation-Potential Interaction

Now, we are considering a special case of the random field treated in §2. Let an intense acoustic noise flux propagate through a crystalline sample, having the form of wave packet with a small angular divergence and a long central wavelength $\lambda_0 : \lambda_0 \gg a$, $a$ being the lattice constant. Then, the displacement of the lattice from its equilibrium position due



to the flux can be written as follows:

$$u(R) = \frac{2}{\sqrt{N}} \sum_{q,\nu} u_q^\nu e^\nu \cos(qR + \varphi_q^\nu). \tag{17}$$

Here $N$ denotes the number of unit cells in the fundamental volume, $u_q^\nu$ and $\varphi_q^\nu$ are, respectively, the real amplitude and the initial phase of the normal mode $\nu$ with propagation vector $q$ and unit polarization vector $e^\nu$. In accordance with the noise nature of the acoustic flux, the phases $\varphi_q^\nu$ are supposed to be random, statistically independent for various $\nu$ and different $q$, and uniformly distributed in the interval $(0, 2\pi)$.

An acoustic flux travelling in a medium is, as usual, accompanied by an energy flux. The flux intensity of the $\nu$-mode, defined as an average of its energy flux density over the oscillation period, may be given in the form:

$$P_\nu = \frac{2\varrho v_\nu^3}{N} \sum_q q^2 (u_q^\nu)^2, \tag{18}$$

where $\varrho$ means the mass density of the medium, $v_\nu$ is the phase velocity of the sound depending upon the direction of propagation and that of polarization of the mode in question.

It is well known that an acoustic noise flux is also accompanied by force fields acting on the electrons in the conduction band and the holes in the valence band via deformation-potential coupling present in all semiconducting materials, and piezoelectric coupling present in cubic crystals lacking inversion symmetry. The former interaction is proportional to the strain, whereas the latter is proportional to the strain gradient. Consequently, the corresponding fields are shifted in phase by $\pi/2$, and hence their configuration-averaged product must vanish. This means that these interactions are statistically independent, which permits them to be treated separately just as in electron-phonon scattering problems of the transport theory.[22] Recently, the piezoelectric noise field has been thoroughly examined.[14] In the present paper we are dealing with the acoustic noise field connected with deformation-potential coupling.

It has been pointed out[23] that the hydrostatic component of the strain may bring about a shift of the band gap, whilst its shear component leads only to a split of subbands in the valence band. This allows us to ignore the shear deformation potentials when regarding the influence of the band-gap fluctuations on Auger recombination. The deformation-potential interaction is then created merely by the longitudinal mode of acoustic waves, giving rise to sample dilation. Furthermore, it has been usually assumed that the deformation-potential interaction is screened by free carriers in exactly the same way as long-range interactions, e.g. those arising from charged impurities or piezoelectric coupling.[22,24-26] This assumption was already derived rigorously.[7,8,27] As a result, the deformation-potential energy of the charge carriers is to be taken in the following form:

$$U_l(\boldsymbol{R}) = -\frac{2\Xi_l}{\sqrt{N}}\sum_q \frac{q}{1+(qr_D)^{-2}} u_q^L \sin(\boldsymbol{qR}+\varphi_q^L). \tag{19}$$

Here $\Xi_l$ ($l = C,\ V$) stand for the deformation-potential constants referring to the conduction and valence bands, respectively. $r_D$ is the Thomas-Fermi screening length, which for non-degenerate carrier statistics is identified with the Debye-Hückel radius:

$$r_D = \sqrt{\frac{\varepsilon T}{e^2 n}}, \tag{20}$$

where $e$ means the electron charge, $\varepsilon = \kappa\varepsilon_0$ means the static dielectric constant (SI units will be employed), $n$ is the majority-carrier concentration.

In accordance with the chaotic nature of the phases $\varphi_q^L$ figuring in the expression (19), the deformation-potential interaction accompanying an acoustic noise flux is random. In addition, this expression may be readily shown to satisfy the Bogoliubov theorem[19,28] and hence the acoustic noise field associated with deformation-potential coupling obeys Gaussian distribution. This random field seems to be of some interest in regard to optical transitions.[20,28] Finally, the non-random parameter defined by eq. (12) is now given only in terms of the deformation-potential constants as

$$\gamma = \frac{\Xi_V}{\Xi_C}. \tag{21}$$

Now, we turn to the binary correlation function defined by eq. (1). Upon making use



of the standard procedure[20] we get

$$\Psi_{ll}(\boldsymbol{R}-\boldsymbol{R}') = \frac{2\Xi_l^2}{N}\sum_q \frac{q^2}{[1+(qr_D)^{-2}]^2}(u_q^L)^2\cos[\boldsymbol{q}.(\boldsymbol{R}-\boldsymbol{R}')]. \tag{22}$$

Next, inserting the function (22) into eqs. (3), (4) and employing eq. (18), we are in a position to represent the mean squares of the potential fluctuations and the strength of the acoustic noise field in terms of the flux intensity $P_L$ of the longitudinal mode of the sound waves:

$$\psi_{1l} = \frac{\Xi_l^2 P_L}{\varrho v_L^3}\frac{1}{[1+(\lambda_0/2\pi r_D)^2]^2} \tag{23}$$

and

$$\psi_{2l} = \frac{\Xi_L^2 P_L}{\varrho v_L^3}\frac{2\pi^2}{\lambda_0^2[1+(\lambda_0/2\pi r_D)^2]^2}. \tag{24}$$

Here $\lambda_0$ means, as before, the central wavelength of the acoustic waves, $v_L$ is the sound velocity of the longitudinal mode.

Lastly, we return to the semiclassical condition (2). With the use of eqs. (23), (24) it may be rewritten as follows

$$\frac{\pi^2\hbar^2}{2m_l}\sqrt{\frac{\varrho v_L^3}{\Xi_l^2 P_L}}\left[\frac{1}{\lambda_0^2}+\frac{1}{(2\pi r_D)^2}\right] \ll 1, \quad (l = C,\ V). \tag{25}$$

This inequality reveals that the acoustic noise field in a given sample will behave semiclassically at high flux intensity and long central wavelength of the acoustic waves as well as with large screening radius, which corresponds to high temperature and low carrier concentration as seen clearly from eq. (20).

As quoted above, the acoustic and piezoelectric noise fields are statistically independent so that the disorder effect caused by them both simultaneously is evidently fixed also by eq. (13), however, the random parameter is now given by:

$$\psi_i = \psi_i^{AC} + \psi^{PE}, \quad (i = e,\ h). \tag{26}$$

Here $\psi^{PE}$ denotes the mean square potential fluctuation of the random piezoelectric field, which depends strongly on the directions of its propagation and polarization. For the case when the acoustic noise travels in the direction [110] only those transverse waves will be piezoelectrically active that have their polarization in the direction [001], yielding the mean square potential fluctuation:[14]

$$\psi^{PE} = \left(\frac{ee_{14}}{2\pi\varepsilon}\right)^2 \frac{P_T}{\varrho v_T^3} \frac{\lambda_0^2}{[1+(\lambda_0/2\pi r_D)^2]^2}. \tag{27}$$

Here $e_{14}$ is the piezoelectric stress constant, $P_T$ and $v_T$ are the flux intensity and the sound velocity of the [110] transverse mode, respectively.

Neglecting the difference between the velocities of the longitudinal and transverse waves ($v_L \sim v_T$), then by means of eqs. (14), (23) and (27), we can arrive at a crude estimation of the ratio between the random parameters characterizing the acoustic and piezoelectric noise fields of equal flux intensities ($P_L = P_T$):

$$\frac{\psi_i^{AC}}{\psi^{PE}} \sim \left(\frac{2\pi\varepsilon\alpha_i\Xi_C}{ee_{14}\lambda_0}\right)^2, \quad (i = e,\ h). \tag{28}$$

This indicates that the influences of the noise fields associated with deformation-potential and piezoelectric interactions on Auger recombination become competable at short central wavelength, i.e. high central frequency of the acoustic waves. For instance, we find for a sample based on GaAs: $\lambda_0 \sim 10^{-5}$cm, i.e. $\omega_0 \sim 3\times10^{11}$rads$^{-1}$, with shorter wavelengths the acoustic noise field is predominant. The disorder effect due to this field on Auger processes will be illustrated in the following.

## §4. Effect of an Acoustic Noise Field on Auger Recombination

Let us apply the theory developed in §§2 and 3 to examine the influence of an acoustic noise field connected with deformation-potential coupling on Auger processes. Putting eqs. (20), (23) into eqs. (13), (14) yields immediately the following simple expression of the ratio of the Auger coefficients for a sample with and without noise:

$$\frac{C_i}{C_{i0}} = \exp\left[\frac{\alpha_i^2\Xi_C^2 P_L}{2T^2\varrho v_L^3(1+e^2\lambda_0^2 n/4\pi^2\varepsilon T)^2}\right], \quad (i = e,\ h). \tag{29}$$



So, the disorder effect is generally found to depend strongly on such experimental conditions as the flux intensity, central wavelength and velocity of the sound waves as well as the carrier concentration and temperature of the sample. It should be noticed that this effect exhibits an exponential dependence on the flux intensity and, in addition, it becomes of more importance at low temperature.

Just as an example, we chose GaAs with material parameters listed in Table I.[29] We have carried out the numerical calculations of the Auger coefficient ratios $C_e/C_{e0}$ for the CHCC process (Fig. 3) and $C_h/C_{h0}$ for the CHSH process (Fig. 4) taking place in a sample through which an intense acoustic noise flux propagates in the direction [110]. These ratios were plotted as functions of flux intensity in a range of $10^7$ to $10^{10}$ Wm$^{-2}$ for different central wavelengths of the acoustic waves ($\lambda_0 = 10^{-5}$ and $10^{-4}$ cm) and with various values of temperature ($T = 77$ and 300 K) and carrier concentration ($n = 10^{20}$, $10^{21}$, $10^{22}$ and $10^{23}$ m$^{-3}$).

From the results thus obtained we may come to the following conclusions:

(i) An examination of Figs. 3 and 4 shows that the acoustic noise field is able to raise the Auger recombination by up to several orders of magnitude at high flux intensity ($P_L \geq 10^9$ Wm$^{-2}$), in particular, with short acoustic wavelength ($\lambda_0 = 10^{-5}$ cm), low temperature ($T = 77$ K) and small carrier concentration ($n \leq 10^{21}$ m$^{-3}$). The reason for the dramatic enhancement of the Auger processes owing to random deformation-potential interaction is twofold. First, analogous to the case of random piezoelectric coupling, there are more numerous electron states of large occupation probability which participate in the Auger transition. These states lie near to the band edges of the conduction and valence bands and, especially, on the density-of-state tails in the band gap, which arise from the noise-induced disorder. Second, it follows from Table I a feature of the deformation-potential coupling in GaAs that its non-random parameter is negative: $\gamma < 0$. This means that in the case in question the band edges of the conduction and valence bands are shifted in opposite directions. As a consequence, there exist in the sample some space regions where the local band gap is diminished. This leads to an effective reduction of the threshold energy for Auger transition and, therefore, to an enhancement of it ($\alpha_i^2 > 10$).

(ii) It is well known that the Thomas-Fermi screening of the acoustic interaction due to free carriers gives small corrections to electron mobility, and hence it may not be included in the transport theory[22]. On the contrary, screening is found to assume vital importance in connection with Auger recombination in an acoustic noise field, reducing the disorder effect remarkably in favour cases. It is evidently seen from eq. (23) that the screening is specified by a relative comparison of the central wavelength of the sound waves with the Debye-Hückel radius: $\lambda_0/2\pi r_D$. Then, it results that screening is more important at long wavelength, i.e. low frequency of the acoustic waves and, in addition, at large carrier concentration and low temperature of the system. In the case of $\lambda_0 = 10^{-4}$ cm it becomes so strong that the noise-field effect is almost totally eliminated by free carriers of concentration $n \geq 10^{22}$ m$^{-3}$ at any temperatures used.

(iii) A comparison of Figs. 3 and 4 indicates that the influence of an acoustic noise field on the CHCC process and that on the CHSH process are comparable in magnitude (strictly, the latter effect is a little larger than the former). This can be explained by the fact that the effective mass ratios entering eqs. (15) and (16) are, as mentioned in §2, small and the non-random parameter of GaAs is $\gamma \sim -1$ so that we have $\alpha_e \sim \alpha_h$.

In closing, it is interesting to discuss some practical applications of the above considerations. On one hand, Eqs. (15), (16) and (29) might offer a useful tool for investigating acoustoelectric domains, namely to evaluate the flux intensity of the longitudinal mode - one of the parameters characterizing the domains, directly from Auger lifetime measurements besides optical experiments.[18] This is clearly of more significance in the case when there is no piezoelectric interaction, e.g. in non-piezoelectric materials. On the other hand, it is well known that by means of pressure experiments in semiconductor optics we can measure only relative shifts of the band edges of the conduction and valence bands. Then, it is merely possible to determine the sum of the relevant deformation-potential



constants $\Xi_C + \Xi_V$.[23] Therefore, in most theoretical descriptions of electron-phonon scattering problems in the transport theory some deformation potentials have to be referred to as adjustable parameters. The study of Auger recombination in an acoustic noise field could suggest a possibility to estimate the ratio $\gamma = \Xi_V/\Xi_C$ so that it might be possible to fix separately the deformation potentials.

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Table I. Material parameters of GaAs used.

| | | |
|---|---|---|
| Effective masses: | $m_C$ ($m_e$) | 0.067 |
| | $m_H$ ($m_e$) | 0.45 |
| | $m_S$ ($m_e$) | 0.154 |
| Deformation potentials: | $\Xi_C$ (eV) | +7.0 |
| | $\Xi_V$ (eV) | −8.9 |
| Static dielectric constant | $\kappa$ | 13.18 |
| Lattice mass density | $\varrho$ ($10^3$ kgm$^{-3}$) | 5.36 |
| Sound velocity of the [110] longitudinal mode | $v_L$ (kms$^{-1}$) | 5.21 |



## Figure Captions

**Fig. 1.** Conduction band Auger process CHCC due to e-e collision.

**Fig. 2.** Valence band Auger process CHSH due to h-h collision.

**Fig. 3.** Ratio of the Auger coefficients $C_e/C_{e0}$ for the CHCC process in the presence and in the absence of an acoustic noise flux propagating in the direction [110] against flux intensity $P_L$ at low temperature ($T$ = 77 K: full curves) and room temperature ($T$ = 300 K: broken ones). The label a corresponds to the central wavelength of the sound waves $\lambda_0 = 10^{-5}$ cm and the b to $\lambda_0 = 10^{-4}$ cm; the subscripts 1, 2, 3 and 4 refer to different carrier concentrations: $n = 10^{20}$, $10^{21}$, $10^{22}$ and $10^{23}$ m$^{-3}$, respectively. The curves labelled by $a_3$ and $b_1$, $a_4$ and $b_2$ are identical, indicating equal screening owing to free carriers. The full curve $b_3$ and the broken lines $b_3$, $b_4$ almost coincide with the abscissa, showing the absence of the disorder effect.

**Fig. 4.** Ratio of the Auger coefficients $C_h/C_{h0}$ for the CHSH process in a sample with and without an [110] acoustic noise flux versus flux intensity $P_L$. The interpretation is exactly the same as given in Fig. 3.

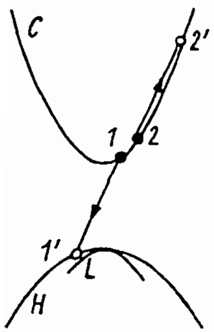


Fig. 1

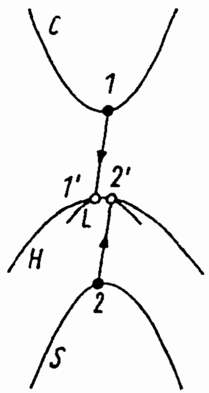


Fig. 2

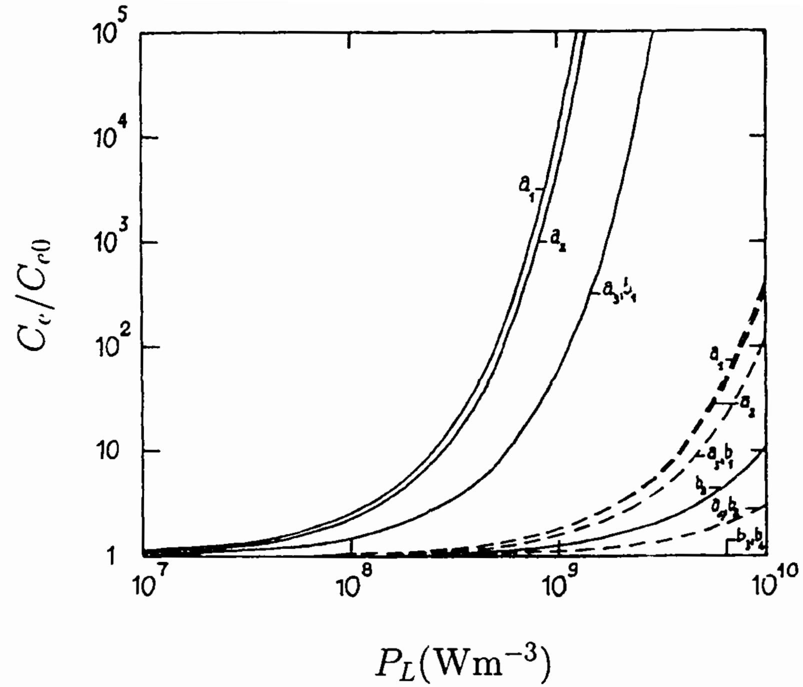


Fig. 3

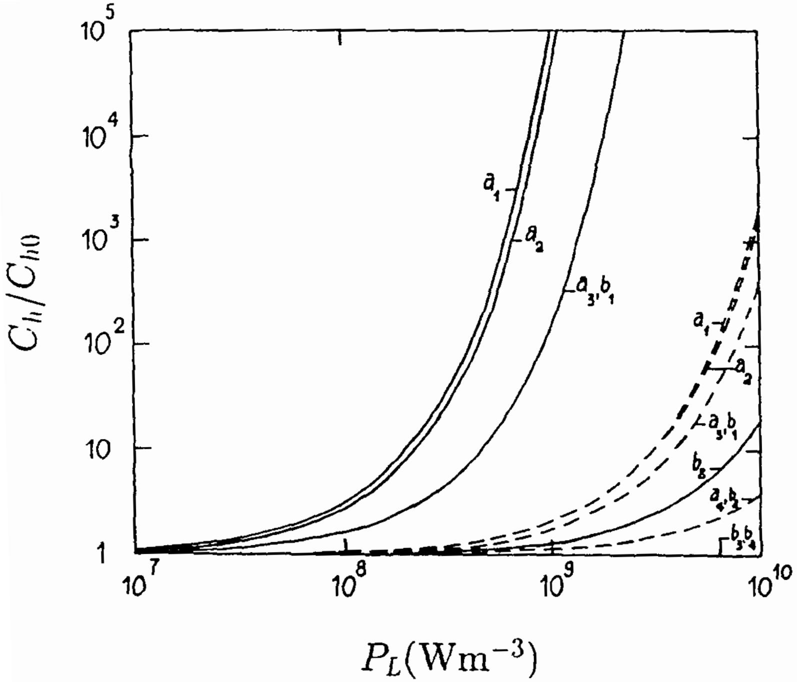
$10^5$
$10^4$
$10^3$
$10^2$
10
1
$10^7$
$10^8$
$10^9$
$10^{10}$
$C_h/C_{h0}$
$P_L(\mathrm{Wm}^{-3})$
$a_1$
$a_2$
$a_3, b_1$
$a_1$
$a_2$
$a_3, b_1$
$b_2$
$a_4, b_3$
$b_3 b_4$

Fig. 4