Interband and impurity breakdown in an electric field in semiconductors with an impurity band

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(Submitted 22 June 1993)
Zh. Eksp. Teor. Fiz. **104**, 4094–4106 (December 1993)

This work is the first theoretical investigation of the hot-electron transport and electric breakdown in a semiconductor with a band of delocalized extrinsic states. The case when bands of forbidden states separate the impurity band from the intrinsic bands of the crystal is studied. The contribution of all three groups of current carriers from the conduction, valence, and impurity bands, including the change in their densities due to impact ionization in a strong electric field, is taken into account. It is shown that a distinctive combined overheating mechanism of *s*-type negative differential conductance, owing to intercoupled changes in both the density and mobility of the carriers, arises in such a system. In some cases two sections with *s*-type negative differential conductance can appear on the current-voltage characteristic. The process of change of the carrier density in each band incorporates features of both impurity and interband breakdowns.

1. INTRODUCTION

The vast majority of works on the theory of hot electrons in semiconductors concern investigations of the properties of carriers occupying a single energy band.[1–4] Much less attention has been devoted, on the whole, to nonequilibrium processes in systems containing several groups of carriers, even though early in the development of hot-electron physics it became clear that these systems have much richer nonequilibrium properties. Indeed, it is the presence of several electron groups in a multivalley material that is responsible for the most pronounced classical effects of hot electrons—the Gunn effect and the Sasaki effect.

Recently, however, investigations of the kinetic properties of nonequilibrium carriers in systems with several types of electronic states have been expanding appreciably. Examples are the investigation of the effect of $\Gamma-L$ and $\Gamma-x$ transitions on the relaxation of hot electrons in GaAs;[5] the study of the transport of hot electrons in quantum wells and wires[6] or in a parallel magnetic field in a bulk material,[7] when carriers from many size-quantized or magnetic subbands participate in the transport; investigations of electron transport under conditions of impurity[8] or interband[9] breakdown, etc.

In the present paper we make the first theoretical investigation of the kinetics of hot electrons in another semiconductor system with several groups of carriers—a narrow-band semiconductor with an impurity band, in which the electron states are delocalized. In this case carriers from three bands—conduction, valence, and impurity—participate in transport. We consider the case when carrier transport in the impurity band proceeds via delocalized states, and it is assumed that the impurity band is relatively narrow and is separated from the initial (intrinsic) bands of the crystal by bands of forbidden states. Such extrinsic bands have been observed, for example, in samples of lead chalcogenides $Pb_{1-x}Sn_xTe$ and $Pb_{1-x}Sn_xSe$ irradiated with fast electrons.[10,11] If the density of irradiation-induced defects is significant, then the electronic states of the defects are, apparently, hybridized, since the observed mobility μ_i in the defect band is $\sim 10^2$ $cm^2/V \cdot sec$, which is very large for extrinsic conduction. At the same time, μ_i is still small compared to the mobility in the intrinsic bands of the crystal ($\mu_e \sim \mu_h \sim 10^4$–$10^5$ $cm^2/V \cdot sec$). Thus the kinetic characteristics of the carrier groups are significantly different, and this significantly influences the behavior of the entire electronic system in strong electric fields. The situation is made even more complicated by the fact that electronic transitions between all three bands and changes in the number of carriers in each band due to impact ionization must be taken into account.

Since a complete description of the transport properties of carriers in extrinsic bands with delocalized states is still an unsolved problem,[12] we shall employ only some general assumptions about these properties. Our aim is to construct a comparatively simple and general approach that would be suitable for describing the basic properties of the experimental system in a strong electric field, irrespective of the specific details of the conductance of the impurity band.

The calculation will be based on the Boltzmann equation in the effective-temperature approximation.[1,2] The high carrier density in both the impurity band and the impurity bands under conditions of electric breakdown can serve as the basis for this approach.

We shall show that the presence of extrinsic carriers in such systems can produce significant features in the current-voltage characteristics, in particular, the possibility of a new mechanism for negative differential conductance (NDC), owing to intercoupled changes in both the density and mobility of the carriers. Electric breakdown, due to impact ionization in a strong field, in the system under consideration incorporates features of both impurity and interband breakdowns, as a result of which two successive sections of *s*-type NDC can arise successively in the

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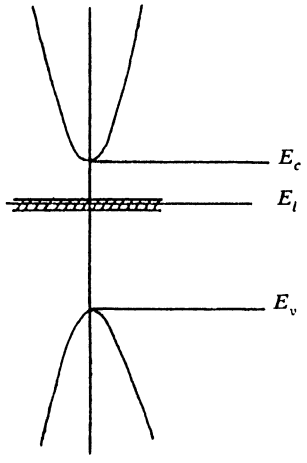

FIG. 1. Energy diagram of a semiconductor with an extrinsic band.

current-voltage characteristic. It is interesting, however, that the stable section separating these two sections in the I-V characteristic corresponds to impurity breakdown.

2. DESCRIPTION OF THE MODEL

In this paper we investigate carrier transport in a constant electric field in a direct-band semiconductor with symmetric ($m_e=m_h$), isotropic, and parabolic dispersion laws in the intrinsic bands of the crystal (conduction and valence). Of course, in real $Pb_{1-x}Sn_xTe$ the spectrum is anisotropic and multivalley, but we shall employ a simplified model, especially since in the effective-temperature approximation, which we employ for calculations, the conductivity of $Pb_{1-x}Sn_xTe$ and $Pb_{1-x}Sn_xSe$ cubic semiconductors is isotropic even under conditions of heating.[10] We employ the parabolic approximation, since we shall study the range of electron temperatures which are low compared to the width of the forbidden band. It is assumed that the forbidden band lies in the gap (Fig. 1), and conduction in this band occurs via delocalized states. The carriers in the impurity band are characterized by mobility μ_i and energy relaxation time τ_i, which are assumed to be constant and independent of the degree of heating of the carriers. This assumption is partially justified by the fact that transport along the impurity band is manifested significantly only in a quite narrow range of electron temperatures. In accordance with the experimental situation, we assume $\mu_i \ll \mu_e$ and $\tau_i \ll \tau_e$, where τ_e is the energy relaxation time of carriers in the bands of the crystal on lattice vibrations, since it can be expected that particles with low mobility in a narrow impurity band are scattered much more strongly by phonons than light carriers in the intrinsic bands. Since we are considering a semiconductor with a symmetric spectrum of intrinsic bands, we assume that the transport characteristics of the carriers—mobility and relaxation time—are identical in these bands.

We assume that the scattering of electrons and holes in the intrinsic bands by lattice imperfections and phonons is quasielastic. This enables us to introduce the corresponding relaxation times for each mechanism, the dependence of these times on the carrier energy being of a power-law character with exponents $(-q)$ and $(1-r)$ for the momentum and energy relaxation times, respectively. The values of q and r for different scattering mechanisms can be found in Refs. 1, 2, and 14.

We shall use the effective-temperature method[1,2] to study the transport of hot electrons in the system described above. This method assumes that the symmetric part of the distribution function for each group of carriers has the Fermi form with some "effective" temperature and quasi-Fermi level. The high carrier concentration in both the impurity and the intrinsic bands under conditions of breakdown can serve as the basis for this approach.

In the semiconductor under study the system of carriers consists of three subsystems: electrons and holes in the intrinsic bands and carriers in the impurity band. In order to determine the field dependence of the heating temperatures and the quasi-Fermi level of each subsystem we employ the condition of electric neutrality and the equations of energy and particle number balance. In the general case the system is characterized by three temperatures T_i, T_e, and T_h and three quasi-Fermi levels F_i, F_e, and F_h for carriers in the impurity band, for electrons in the conduction band, and for holes in the valence band, respectively. Since the masses of the carriers in the intrinsic bands of the crystal are the same,

$$T_e=T_h. \tag{1}$$

We designate the total carrier density in the intrinsic bands by n_b:

$$n_b=n_e+n_h, \tag{2}$$

where n_e is the electron density in the conduction band and n_h is the hole density in the valence band.

With the help of Eqs. (1) and (2) we now write out the system of balance equations for the problem posed above in the stationary, spatially uniform case:

$$\begin{aligned}
&e\mu_e n_b E^2=\frac{T_e-T_0}{\tau_e}n_b+\frac{T_e-T_i}{\tau_{ei}}n_b,\\
&e\mu_i n_i E^2=\frac{T_i-T_0}{\tau_i}n_i+\frac{T_i-T_e}{\tau_{ie}}n_i,\\
&N_i+n_e-n_h=N_0,\\
&R^c_{ci}+R^c_{cv}+R^c_{cvi}=G^c_{ci}+G^c_{cv}+G^c_{cvi},\\
&R^v_{vi}+R^v_{vc}+R^v_{vci}=G^v_{vi}+G^v_{vc}+G^v_{vci},\\
&R^i_{ic}+R^i_{iv}+R^i_{icv}=G^i_{ic}+G^i_{iv}+G^i_{icv}.
\end{aligned} \tag{3}$$

The first two equations are the equations of energy balance for carriers in the intrinsic and impurity bands, respectively. Here E is the intensity of the electric field, T_0 is the lattice temperature, and τ_{ei} and τ_{ie} are, respectively, the energy relaxation times of the intrinsic carriers on impurities and vice versa (as already mentioned, we assume that τ_e and τ_{ei} are identical for electrons and holes in the intrinsic bands). The third equation is the condition of electric neutrality, where $N_i(T_i)$ and N_0 are the electron density in the impurity band at temperature T_i and at $T_i=0$, respectively. The last three equations are the equation of balance

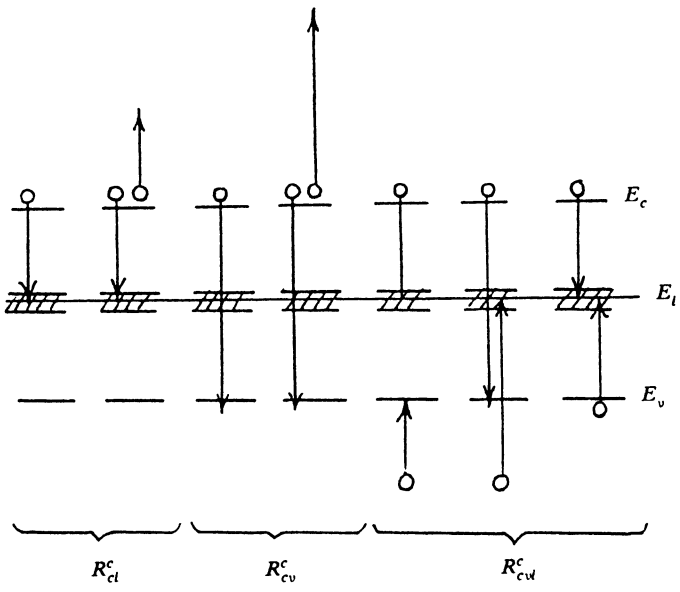

FIG. 2. Diagram of recombination processes in a semiconductor with participation of states from the conduction band. The arrows indicate electronic transitions.

of particle number for each carrier subsystem, only two being independent, since the constancy of the carrier density in any two subsystems implies that the carrier density is constant in the third subsystem. The letters R and G designate the carrier recombination and generation rates, the superscripts indicate the subsystem to which the rates refer, and the subscripts indicate the band states which participate in the given process (c—conduction band, v—valence band, i—impurity band). As an example, Fig. 2 displays a diagram of the recombination processes for the conduction band.

Thus, the system (3) includes five independent equations for determining five unknowns T_e, T_i, F_i, F_e, and F_h; this makes it possible to find, in principle, the field dependences of the densities and effective temperatures as well as the current-voltage characteristics:

$$j=e\{\mu_e(T_e)[n_e(T_e,F_e)+n_h(T_e,F_h)]+\mu_i n_i(T_i,F_i)\}E.$$

In order to solve the system (3), however, it is first necessary to determine the interband-transition rates appearing in it. This is an independent, quite complicated and difficult problem. This is especially true for transitions in which states from the impurity band participate, since the form of the carrier wave functions in the hybridized impurity band is not clear. However, there exists a particular case in which a solution can be found for the equations of balance of particle number without the use of the explicit form of the transition rates. It is this case that we shall consider.

Recombination in narrow-band semiconductors with an impurity band has not been adequately studied. In weakly doped narrow-band materials of the type $Pb_{1-x}Sn_xTe$ and $Pb_{1-x}Sn_xSe$ Auger recombination and multiphonon processes play the main role.[15,16] Since the rate of Auger processes increases as the square of the carrier density in the intrinsic bands and the rate of multiphonon capture is linear in this density, in the presence of breakdown Auger processes start to play the main role in the increase of the electron temperature and growth of the carrier density in the intrinsic bands, so that we shall take into account only these processes. We assume, in addition, that the temperature $T_e \gg \Delta$, where Δ is the width of the forbidden band. Since $\Delta \ll \varepsilon_g$ usually holds, in this range of electron temperatures the particle density in the intrinsic bands can vary over wide limits. The condition $\Delta \ll T_e$ makes it possible to neglect the width of the impurity band when calculating interband impact-ionization and Auger-recombination rates. As a result, the carrier temperature in the impurity band drops out of the equations of balance of interband transitions, and only the temperature T_e of the particles in the intrinsic bands remains in these equations. It is significant that since we take into account only Auger transitions, the lattice temperature also does not appear in these equations. As a result, the fact that T_e characterizes a nonequilibrium state is in no way reflected in the form of the equations of particle number balance. Correspondingly, these equations have the same solution as in equilibrium: The total rate of Auger transitions (including recombination and ionization) vanishes when electrons in all states are described by a single Fermi distribution function F_e. This means that, first,

$$F_e=-F_h=F,$$

and, second, the population of the extrinsic band is determined as

$$N_i=N_0 f_e(E_i,T_e,F)=N_0\frac{1}{\exp[(E_i-F)/T_e]+1}.$$

Here N_0 is the total number of states in the impurity band:

$$N_0=\int_\Delta \rho_i(\varepsilon)d\varepsilon,$$

where $\rho_i(\varepsilon)$ is the density of states in and E_i determines the position of this band (Fig. 1). The quasi-Fermi level F_e can be found from the condition

$$\frac{\int_\Delta f_i(\varepsilon)\rho_i(\varepsilon)d\varepsilon}{\int_\Delta \rho_i(\varepsilon)d\varepsilon}=\frac{N_i}{N_0},$$

as a function of T_e, T_i, and F. Here $f_i(\varepsilon,T_i,F_i)$ is the energy distribution function for the extrinsic carriers. We remind the reader that only the total population of the impurity band can be found from the condition of particle balance, since in seeking the solution of the balance equations we neglect the width of this band.

The initial system (3) ultimately was reduced to three equations. Nonetheless, this system still contains quantities $\tau_{ei}(T_e)$ and $\tau_{ie}(T_e)$ that must be specified. Assuming that the carriers in the narrow extrinsic band are much "heavier" than the particles in the crystal bands, in order to determine the temperature dependence of τ_{ei} and τ_{ie} we employ a result obtained for the energy relaxation of electrons on ions in plasma:[17]

$$\tau_{ei}=\text{const}\, T_e^{1.5}/n_i,$$

$$\tau_{ie}=\text{const}\, T_e^{1.5}/n_b. \tag{4}$$

It follows from Eqs. (4) that

$$\tau_{ei}=\tau_{ie}\frac{n_b}{n_i}. \tag{5}$$

Now we have the system of equations that must be investigated:

$$\begin{aligned} e\mu_e E^2&=\frac{T_e-T_0}{\tau_e}+\frac{T_e-T_i}{\tau_{ei}},\\ e\mu_i E^2&=\frac{T_i-T_0}{\tau_i}+\frac{T_i-T_e}{\tau_{ie}},\\ N_0 f_0+n_e-n_h&=n_0, \end{aligned} \tag{6}$$

where $f_0-f_e(E_i,T_e,F)=N_i/N_0$ is the occupation function (probability) of the impurity band.

We now make one other remark concerning the determination of the density n_i of mobile carriers in the impurity band. It is obvious that n_i approaches zero for both the empty and completely filled bands. In order to take this fact into account, we assume that

$$n_i=N_0 f_0(1-f_0),$$

where f_0 is the occupation function of the impurity band [see Eq. (6)]. This makes it possible to take into account (approximately) the main variation of the conductivity σ_i in the impurity band as a function of filling of the band, using the simple formula $\sigma_i=\mu_i n_i$ and assuming $\mu_i=\text{const}$. Of course, the real energy dependence of the carrier mobility in the impurity band is not clear, but an elementary analysis of the narrow band in the strong-coupling approximation shows that the change in the mobility in the band is small, and for this reason a simple formula for the extrinsic conductivity can be employed as an acceptable approximation. We shall also use this expression for n_i for calculating the relaxation times [see Eqs. (4) and (5)].

3. LIMITING CASES

Before solving the system (6), which, in the general case, must be done numerically, we investigate analytically some particular cases. This will give us an idea about the basic physical processes which are possible in the system under study.

Consider the symmetric situation when the impurity band lies at the center of the gap, and the Fermi level in thermodynamic equilibrium lies in the gap. Under such conditions the temperature shift of the Fermi level can be neglected (we recall that we have $m_e=m_h$), and the system (6) reduces to two energy-balance equations for determining T_e and T_i. We consider first the simplest case, when τ_{ie} and τ_{ei} are the shortest energy-relaxation times, so that frequent interparticle collisions make it possible to establish a single electron temperature in the entire carrier system: $T_e=T_i$. Adding in this case the first two equations (6), we obtain, taking into account Eq. (5),

$$eE^2(\mu_e n_b+\mu_i n_i)=(T_e-T_0)\left[\frac{n_b}{\tau_e}+\frac{n_i}{\tau_i}\right]. \tag{7}$$

In this equation $n_b\sim\exp(-\varepsilon_g/2T_e)$ depends sharply on the heating temperature, while n_i is virtually unchanged. Such different behavior of the densities makes possible a thermal instability. Indeed, let T_0 to be low enough so that $\mu_e n_b(T_0)\ll\mu_i n_i$. Then, obviously, $n_e/\tau_e\ll n_i/\tau_i$, since $\mu_e\gg\mu_i$ and $\tau_e\gg\tau_i$, and in weak fields with $T_e\simeq T_0$ Eq. (7) describes carrier heating in the impurity band. However, n_b increases rapidly with increasing field and electron temperature, and there exists a range of fields such that $\mu_e n_b\gg\mu_i n_i$ but $n_e/\tau_e\ll n_i/\tau_i$. In this range the conductivity and Joule heating of the system are determined by the electrons and holes in the crystal bands, the number of electrons and holes increasing exponentially with increasing T_e, while carriers in the impurity band, where their density remains unchanged, are responsible for transferring energy to the lattice. The thermal instability develops in this range of fields and electron temperatures, since energy flow into the carrier system increases more rapidly than energy is removed. In the I-V characteristic a section with negative differential conductance then appears. Since the system under consideration contains different types of carriers, it is impossible to say unequivocally that the mechanism of instability is of the concentration or mobility type. Actually, the instability arises because the dominant mechanisms of both momentum and energy relaxation change as the carrier density in the intrinsic bands increases.

As E, T_e, and n_b increase further terms $\sim n_b$ start to dominate on both sides of Eq. (7), and the behavior of the system is now determined here by the scattering of particles only in the intrinsic bands, and the presence of an impurity band is not manifested.

We now consider the more general case when the times τ_{ie} and τ_{ei} are not necessarily short, so that T_e may be different from T_i. In this case it is easy to derive from the first two equations of Eqs. (6) the following relation for determining the field-dependence of T_e:

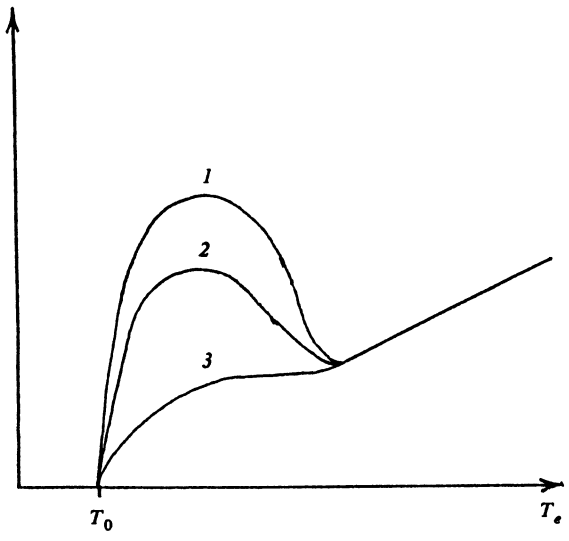

FIG. 3. Temperature dependence of the right-hand side of the relation (8) for different values of the ratio $\alpha=\tau_e/\tau_{ei}$: (*1*) $\alpha\gg 1$, (*2*) $\alpha>1$, and (*3*) $\alpha\sim 1$.

$$eE^2\mu_e\tau_e=(T_e-T_0)\frac{\frac{\tau_{ei}}{\tau_i}+\frac{\tau_e}{\tau_i}+\frac{n_b}{n_i}}{\frac{\tau_{ei}}{\tau_i}+\frac{\mu_i}{\mu_e}+\frac{n_b}{n_i}}. \tag{8}$$

Since, as in the preceding case, the main factor here will be the exponentially rapid increase in $n_b(T_e)$, for simplicity we neglect here the slower temperature variations of the mobilities and assume that the mobilities are constant. Plots of the temperature dependence of the right-hand side of Eq. (8) are displayed in Fig. 3 for different values of the ratio τ_e/τ_{ei} (we assume here that the ratio n_b/n_i with $T_e\simeq\varepsilon_g$ become significantly greater than all other terms in the numerator and denominator of the fraction). It is clearly evident from the figure that negative differential conductance can arise only if τ_{ei} is sufficiently short. Indeed, we have already considered the limit when τ_{ei} and τ_{ie} are the shortest times in the system so that $T_e=T_i$, and we have demonstrated the possibility of negative differential conductance. Conversely, for $\tau_{ei}\gg\tau_e$ the two carrier subsystems are heated independently, and the thermal instability associated with this interaction does not arise.

4. NUMERICAL RESULTS

In the general case when the temperature shift of the quasi-Fermi level must be taken into account, the system (6) is solved numerically.

Solving the first equation in the system (6) for T_i and substituting the result into the second equation, we obtain two equations determining the field dependence of the Fermi level and the electron temperature. It is convenient to write this system in dimensionless variables. All energies are expressed in units of ε_g relative to the center of the forbidden band. All mobilities and times are expressed in units of μ_i and τ_i, respectively. We assume that the energy distribution of the intrinsic carriers is nondegenerate.

We consider the most interesting limit, $\tau_{ei}/\tau_e\ll 1$. In this case the dimensionless equations have the form

$$e^{2\xi/T_e}+\left[\frac{N_c(\varepsilon_g)}{N_0}T_e^{1.5}e^{-1/2T_e}(e^{2\xi/T_e}-1)-\frac{n_0}{N_0}e^{\xi/T_e}\right](e^{\xi/T_e}+e^{\varepsilon_i/T_e})=0,$$

$$F^2=\frac{(T_e-T_0)\left[f_0(1-f_0)+\frac{N_c(\varepsilon_g)}{N_0}T_e^{1.5}e^{-1/2T_e}(e^{\xi/T_e}+e^{-\xi/T_e})\frac{1}{\tau}\left(\frac{T_e}{T_0}\right)^{r-1}\right]}{f_0(1-f_0)+\mu\left(\frac{T_0}{T_e}\right)^q\left[\frac{N_c(\varepsilon_g)}{N_0}T_e^{1.5}e^{-1/2T_e}(e^{\xi/T_e}+e^{-\xi/T_e})+\tau_{ee}\left(\frac{T_e}{T_0}\right)^{1.5}\right]},$$

where $F=E/E_0$ is the external electric field in units of $E_0=(\varepsilon_g/e\mu\tau)^{0.5}$; ξ is the quasi-Fermi level of the intrinsic carriers; $N_0(\varepsilon_g)$ is the effective density of states in the intrinsic bands at temperature ε_g; μ is the mobility of the intrinsic carriers at the lattice temperature T_0; τ is the energy relaxation time of the intrinsic carriers on lattice vibrations at temperature T_0;

$$\tau_{ee}=\frac{\tau_{ei}(T_0,N_0)}{\tau_i},$$

where $\tau_{ei}(T_0,N_0)$ is the energy relaxation time of carriers in the intrinsic bands on particles in the impurity band [see Eq. (4)] with $T_e=T_0$ and $n_i=N_0$.

The numerical results are displayed in Figs. 4, 5, 6, and 7. It was found that the momentum and energy relaxation of the carriers in the intrinsic bands are both due to scattering by deformational acoustic phonons. The current density j is displayed in Figs. 4, 5, and 6 in units of $j_0=(e\varepsilon_g\mu_iN_0^2/\tau_i)^{0.5}$.

As expected (see Sec. 3) the *s*-shaped branch of the *I-V* characteristic is most pronounced in the case of comparatively high rate of energy transfer between carriers in the impurity and intrinsic bands (Fig. 4). The position of the impurity band is also significantly reflected in the form of the $I-V$ characteristic. The point is that after breakdown the quasi-Fermi level F_e moves toward the center of the gap, and it can either pass through the entire impurity

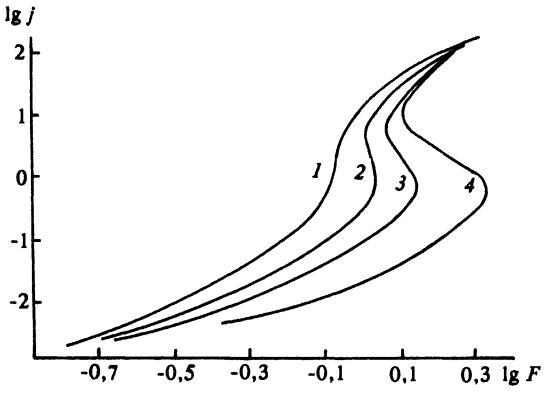

FIG. 4. *I-V* characteristics of a semiconductor with an impurity band at the center of the gap ($E_i=0$). The characteristics were calculated for the parameters $N_c(\varepsilon_g)/N_0=1000$, $n_0/N_0=0.1$, $T_0=0.05$, $0.05<T_e<0.5$, $\mu=20$, $\tau=200$, $q=0.5$, $r=1.5$, and for different values of τ_{ee}: (*1*) $\tau_{ee}=2$; (*2*) $\tau_{ee}=1$; (*3*) $\tau_{ee}=0.5$; (*4*) $\tau_{ee}=0.1$.

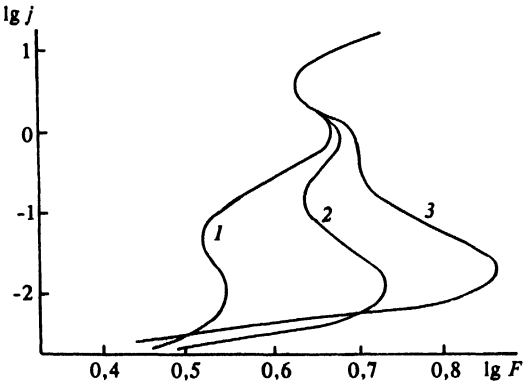

FIG. 6. *I-V* characteristics of a semiconductor with an impurity band at the center of the gap ($E_i=0$). The characteristics were calculated for the parameters $N_c(\varepsilon_g)/N_0=10$, $T_0=0.05$, $0.051<T_e<1$, $\mu=100$, $\tau=100$, $q=0.5$, $r=1.5$, $\tau_{ee}=0.001$, and for different initial occupation of the impurity band: (*1*) $n_0/N_0=0.03$, (*2*) $n_0/N_0=0.06$, (*3*) $n_0/N_0=0.1$.

band or, conversely, leave the band in the direction of the closest boundary. The form of the *I-V* characteristic in these cases is different (Fig. 5).

An interesting situation obtains if after breakdown develops the energy exchange time between two carrier subsystems is the shortest energy relaxation time in the system. If in this case the initial degree of occupation of the impurity band is low ($f_0 \ll 1$), then two breakdown processes develop in the system as the electric field and the heating increase: an impurity process, which results in higher carrier density in the extrinsic band, and an interband process, i.e., rapid increase of the number of electrons and holes in the conduction and valence bands, respectively. In this case the *I-V* characteristic has the form shown in Fig. 6. The mechanism responsible for the appearance of both unstable sections is the same here as the mechanism described above (Sec. 3). Both sections appear due to rapid growth of the carrier density in the intrinsic bands as T_e increases under the condition that the number of electrons in the impurity band, which give rise to energy relaxation of the electron system, remains unchanged. The latter situation occurs both in fields up to the appearance of impurity breakdown and in fields when breakdown has already been completed so that the occupation of the impurity band has reached its maximum value $f_0=1/2$ for the impurity band lying at the center of the gap. The stable intermediate branch, however, is manifested at electron temperatures at which impurity breakdown develops. Since in this case the electron density in the impurity band increases rapidly with increasing T_e (Fig. 7), the flow of energy from them into the lattice also increases rapidly, and this stabilizes the system in this region. It is significant that impurity breakdown, i.e., rapid growth of the carrier density in the impurity band, starts in the electron temperature range where conductivity is determined by particles in the intrinsic bands. This circumstance, which makes possible the existence of two *s*-shaped sections in the *I-V* characteristic, is associated with the existence of the large parameter $\mu_e/\mu_i \gg 1$.

Unfortunately, existing information about carrier energy relaxation processes in materials of the type

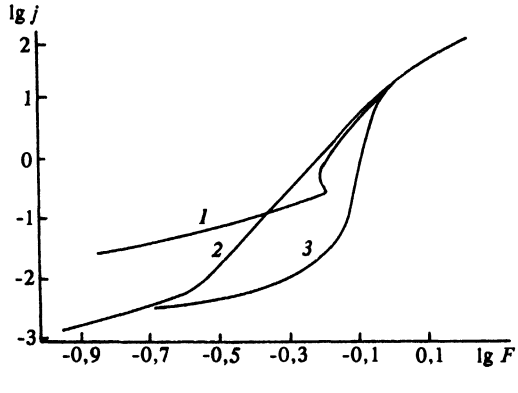

FIG. 5. *I-V* characteristics of a semiconductor with an impurity band. The characteristics were calculated for the same set of parameters as in Fig. 4 but for $\tau_{ee}=2$. (*1*) $n_0/N_0=0.1$, $E_i=-0.25$; (*2*) $n_0/N_0=0.1$, $E_i=0.25$; (*3*) $n_0/N_0=0.5$, $E_i=0$.

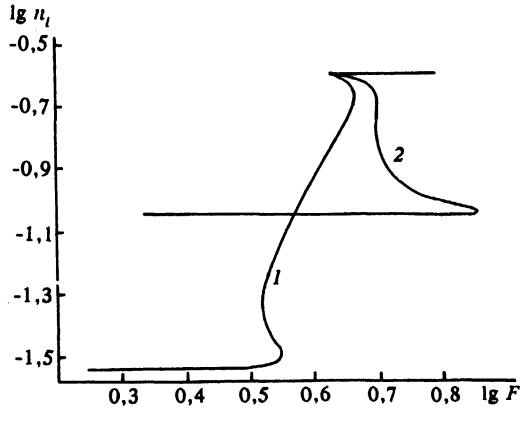

FIG. 7. Field dependences of the carrier density in an impurity band ($E_i=0$). The calculations were performed for the same set of parameters as in Fig. 6 and with (*1*) $n_0/N_0=0.03$ and (*2*) $n_0/N_0=0.2$.

$Pb_{1-x}Sn_xTe$ or $Pb_{1-x}Sn_xSe$ (Ref. 18) is insufficient and does not permit estimating reliably the times τ_e, τ_i, and τ_{ei}. For this reason it is difficult to talk about the possibility of the proposed mechanism in these materials.

Thus the existence of an impurity band of delocalized states in a semiconductor leads to the possibility of a new mechanism for the formation of *s*-type negative differential conductance, and to unusual parallel development of impurity and interband breakdown processes, as is reflected in the form of the *I-V* characteristic which in turn can include two *s*-shaped sections of negative differential conductance. It is interesting that in this case impurity breakdown stabilizes the system.

We thank S. D. Beneslavskii for reading the manuscript and making helpful remarks and I. P. Zvyagin and A. G. Mironov for fruitful discussions. This work is partially supported by grants from the Fundamental Research Fund of Russia and the American Physical Society.

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Translated by M. E. Alferieff