Kinetics of electron capture at *DX* centers in AlGaAs under isotropic compression

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Using the results of direct (real-time) studies of the kinetics of thermally-activated electron capture by *DX* centers in AlGaAs:Te, we show that the reason for the nonexponential nature of the capture process is motion of the quasi-Fermi level for metastable electrons, and in the case of a degenerate electron gas, additional broadening of the thermal activation barrier. We have devised a method for correctly determining the height of the thermally activated barrier, taking into account its dependence on the electronic Fermi energy. We propose a criterion for applicability of the kinetic equation used to describe the process. The results we obtain indicate that the *DX* center is in a negatively charged state.

1. INTRODUCTION

The term "*DX* center" refers to special states of a donor impurity in AlGaAs which give rise to so-called persistent photoconductivity. This photoconductivity is identified by the following features. Let the semiconductor be cooled in the dark to a low temperature. If its conductivity increases upon subsequent illumination and then remains unchanged for a long time after the illumination is switched off, we call this phenomenon persistent photoconductivity.[1] In a number of cases the change in photoconductivity can be orders of magnitude and last for an indefinitely long time.

The state of the *DX* center is a deep trap. Under illumination this trap is ionized, and electrons metastably fill the conduction band, giving rise to persistent photoconductivity. The *DX* center differs fundamentally from a number of other traps by the fact that it does not include within itself any structural defects other than the donor substitution itself. At the present time we do not view the *DX* centers as some sort of structural complex, but rather as a donor state with special properties. It can be created by donors belonging either to group IV or group VI. In the lattices of GaAs or AlGaAs, the same substitutional donor atom can have both *DX*-center states and ordinary quasihydrogenic states. The term "*DX* center" itself has a historical origin.

A commonly held opinion at this time is that a *DX* center is a donor state that is subjected to strong lattice relaxation,[2–4] i.e., the donor atom and its nearest neighbors are displaced (reversibly) from their symmetric positions at the lattice sites. Therefore, free-electron states (in the Γ valley) are separated from the localized state (the *DX* center) by an energy barrier. Since overcoming this barrier requires a rearrangement of atoms in real space, tunneling between these states is negligibly small. Therefore, at low temperatures electrons can metastably fill the Γ valley over a long period of time. At higher temperatures it becomes possible for thermally activated capture of free electrons to take place at the *DX* center: that is, the persistent photoconductivity undergoes relaxation.

In contrast to many other aspects of the physics of *DX* centers, the kinetics of electron capture by these centers (i.e., the relaxation of the persistent photoconductivity) has been studied very incompletely up to the present. This process is strongly nonexponential, so that the concept of a relaxation time cannot be applied to it; in addition, its study by the standard indirect methods [e.g., deep-level transient spectroscopy, or DLTS (Ref. 5)] is extremely difficult. The use of these methods requires some initial assumption about the form of the kinetic equation used to describe the process, and the results obtained depend strongly on these assumptions. Experimental results from DLTS investigations of electron capture by *DX* centers are quite contradictory.[6–8]

In principle, direct study of the relaxation of persistent photoconductivity in real time can give a great deal of information about the details of the process; however, here too the interpretation of the results is quite complicated. For example, the experimental relaxation curves presented by many investigators[9–14] are well-described by a logarithmic dependence on time. However, solutions of this kind can arise from very different kinetic equations. Therefore, the question arises of how to justify the use of some particular kinetic equation; as a rule, there is no answer to this question.

The most detailed experimental studies of persistent photoconductivity relaxation were carried out by Mooney *et al.*[10,11] In these studies, the relaxation curves, which are plotted at constant temperature, are approximated by the numerical solution to a kinetic equation, which is obtained by taking into account two important sources of nonexponential behavior: shifting of the free-electron Fermi level during the relaxation process, and broadening of the thermally activated relaxation barrier. As fitting parameters these authors used the height and width of the barrier, which were the same for the entire set of curves plotted at different temperatures. It was found that the height of the barrier depended strongly on the content of Al in $Al_xGa_{1-x}As$, and that the results obtained were in good agreement with DLTS data given by the same authors in Ref. 6. However, it should be noted that the accuracy of the analysis in this case could not have been high, first of

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all in view of the equivalence of certain fitting parameters, and secondly due to a possible contribution from additional (parasitic) processes.

In contrast to the authors of Ref. 11, Mosser *et al.*[14] analyzed not the relaxation curves themselves but rather their time derivatives, giving them as functions of the Fermi energy of the electron gas. This allowed them to obtain a better match with the kinetic equation for relaxation, and to better distinguish the parameters entering into it. Their investigations were carried out using AlGaAs:Si.

The task of this paper is to study in detail the kinetics of relaxation of persistent photoconductivity in AlGaAs:Te; in it we develop an approach analogous to Mosser *et al.* We seek to identify the kinetic equation by starting from our measurements, i.e., to give its form an experimental basis rather than simply determining the parameters entering into it. With this goal in mind we propose a criterion that can verify the applicability of our approach. In previously published papers,[10–15] the relaxation of a degenerate electron gas was considered. In this paper, we use isotropic pressure (which acts on the band structure of the sample; see Ref. 16) to investigate the relaxation of nondegenerate metastable electrons as well. Furthermore, we attempt to study the relaxation of persistent photoconductivity of a special "activated" form,[17] in which high pressures cause the donor level X^*, which belongs to the lateral X-valley of the conduction band, to be located below the bottom of the Γ valley in energy.

Finally, when speaking of DX centers, we cannot avoid touching on the question of their charge state. In past years, the assumption was made[18] that a donor in the DX-center state is negatively charged (DX^-), capturing not one but two electrons. At present, direct experimental confirmation of this fact has been obtained only for Ge impurities.[19] For other impurities, from both the IV- and VI-groups, the results of various indirect measurements argue in favor of the DX^- model;[14,20–22] however, because of a lack of unambiguous proof, the charge of the DX center remains a subject of discussion. Our results also indicate a negative charge state of the DX center.

2. EXPERIMENTAL METHOD

Our measurements were made on a sample of $Al_xGa_{1-x}As$:Te (with $x_{Al}=0.29$), grown by the method of liquid-phase epitaxy on an insulating GaAs substrate. The sample was intentionally made with a large thickness—12 μm—in order to decrease the influence of surface effects, which distort the picture of relaxation of the persistent conductivity. The concentration of Te in the sample was $2\cdot10^{18}$ cm^{-3}, the electron mobility was ~500 cm^2/V·s. The concentration of Al was determined from the low-temperature photoluminescence spectrum. A Hall bridge was prepared on the sample using photolithography. Ohmic contacts made from In were annealed in vacuum over a period of 10 minutes at a temperature of 360 to 380 °C.

To create isotropic quasihydrostatic compression at low temperatures (4.2 to 100 K), we used an autonomous low-temperature fixed-pressure chamber with current leads.[23,24] The value of the pressure was determined based on the superconducting transition temperature of a Sn manometer. The chamber with the sample was placed in a vacuum bottle, which in turn was placed in a helium cryostat inside a superconducting solenoid. To heat the chamber, a manganin-wire oven was wrapped around it. The sample was illuminated with a GaAs photodiode; temperature was measured using a TBA-brand calibrated thermistor. Both the photodiode and thermistor were placed within the chamber directly on the surface of the sample. This procedure ensured that the temperatures of the sample and thermometer were equal. The current through the oven was regulated by hand. We succeeded in maintaining the temperature constant to an accuracy of 0.005 K when necessary; its absolute value was determined to an accuracy of ~0.1 K.

The resistance (or Hall resistance) of the sample was measured using a nonheating AC current (0.3 to 1 μA, ~180 Hz) in a four-point scheme and a PAR 5207 synchronous detector (lock-in amplifier) with a symmetric input. The voltage source we used was a low-frequency GZ-118 oscillator. The current was stabilized by a load resistance of 10 MΩ (for a characteristic sample resistance of tens of ohms to a few kilohms). The signal from the lock-in was fed through a digital voltmeter to a universal input for a personal computer.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Relaxation of persistent photocurrent and charge state of *DX* centers

The algorithm for our measurements consisted of the following. At a certain fixed temperature T we illuminated the sample until we obtained the maximum persistent photocurrent possible for the available power and illumination geometry. After switching off the illumination, we measured the sample resistance as a function of the real time $R_{xx}(t)$ at constant T. The course of each relaxation curve lasted from 20 to 60 min. Before being used, the sample was calibrated by determining the Hall mobility of free electrons as a function of their concentration and temperature. Each relaxation curve was converted into a dependence of the Hall concentration on time, $n_H(t)$. In practice each trace was plotted over a limited range of n_H because the relaxation becomes too slow. In order to broaden the admissible limits of n_H, in a number of cases we gently heated the sample after 50 to 60 minutes of plotting for a brief period of time (in this case the relaxation is accelerated) and then rapidly cooled it to the previous T; this allowed us to obtain additional points on the relaxation curve. The operating range of T was 50 to 100 K, with temperature steps of 1 to 2 K.

The measurements were performed at pressures of 1 bar, 4 and 8 kbar. At fixed pressure the entire range of the free-electron concentration, and accordingly the Fermi energy, is specified by the band structure of the sample: the lower limit of E_F is determined by the mutual positions of the Γ valley and the DX level, while the upper limit is

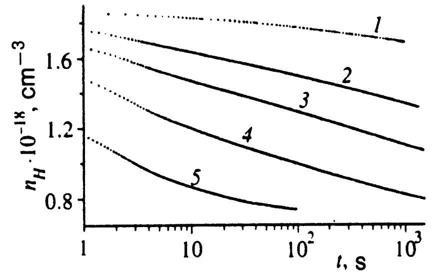

FIG. 1. Characteristic examples of experimental curves for the relaxation of the Hall concentration of electrons, n_H, in real time for a sample under a pressure of 1 bar for various temperatures: *1*) 63.0 K, *2*) 73.3 K, *3*) 79.6 K, *4*) 88.1 K, *5*) 99.8 K.

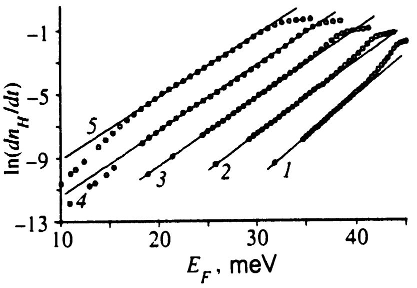

FIG. 3. The same under a pressure of 4 kbar: *1*) 66.6 K, *2*) 71.1 K, *3*) 75.4 K, *4*) 79.6 K, *5*) 84.2 K.

determined by the positions of the Γ valley and the pinning donor level X^* belonging to the X valley. For $P=1$ bar and $P=4$ kbar, both levels (DX and X^*) are in resonance with the Γ valley; for $P=8$ kbar the DX level drops below the Γ valley bottom. Therefore, in the first two cases we observe relaxation of a degenerate gas of metastable electrons, while in the last case a transition occurs from a degenerate to a nondegenerate electron gas during the relaxation.

Figure 1 shows examples of experimental relaxation curves of $n_H(t)$, which are plotted at constant temperature. The function $n_H(t)$ is close to logarithmic. However, it is an extremely complicated task to extract any information about the parameters of the relaxation process from the simple curves $n_H(t)$ in view of the large number of equivalent parameters involved. To separate them, we used the following approach. The curves $n_H(t)$ we obtained were smoothed and differentiated. After this, we constructed the dependence of the relaxation rate dn_H/dt on some particular parameter of the electron gas (the Fermi energy, or temperature) for fixed values of the other parameters.

Figures 2 to 4 show examples of the dependence of dn_H/dt on E_F (at various pressures) on a logarithmic scale. Its important feature is the presence of a clearcut linear portion over a wide range of E_F. This implies that $dn/dt \propto \exp(\alpha E_F/kT)$, which is characteristic of a thermally activated process. We assume that one process dominates—thermally activated capture of electrons by DX centers—in the range where the process is linear. The deviations of the dependence from linear (at the beginning and end of relaxation) indicate the presence of additional processes. Near the lower limit of E_F (at a specific pressure), there is an obvious increase in the contribution from emission of electrons from the DX center. The origin of the additional relaxation process observed immediately after switching off the illumination is not entirely clear. Perhaps it may be connected with, e.g., recombination of spatially separated carriers with different signs.[9,25,26]

Thus, only demonstrably linear portions of the experimental curves $\ln(dn_H/dt) \propto E_F$ correspond to a single relaxation process. If we assume that capture of electrons by DX centers takes place in a thermally activated fashion via an intermediate "barrier" state,[10,11] which in thermodynamic equilibrium is filled along with all the other electron levels (except the DX center), and neglect possible broadening of the barrier, the kinetic equation has the form[11]:

$$dn_H/dt = -\kappa N_D^+ \exp[-(E_B - \alpha E_F)/kT]. \qquad (1)$$

Here N_D^+ is the number of ionized donors and E_B is the barrier height measured from the bottom of the conduction band. At each instant of time, capture takes place through an effective thermally activated barrier $E_B^* = E_B - \alpha E_F$, which has a completely specified height for a given E_F. Because E_B^* is always much larger than kT, the occupation of the "barrier" state obeys Boltzmann statistics. E_B^* in-

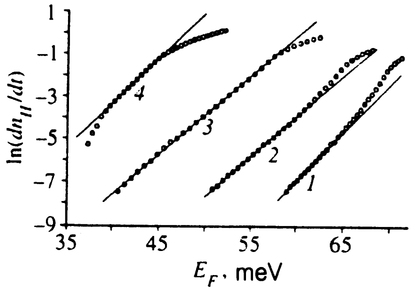

FIG. 2. Examples of the dependence of the relaxation rate for free electrons, dn_H/dt (on a logarithmic scale) on the Fermi energy of the electron gas under a pressure of 1 bar for various temperatures: *1*) 73.3 K, *2*) 79.6 K, *3*) 88.1 K, *4*) 99.8 K.

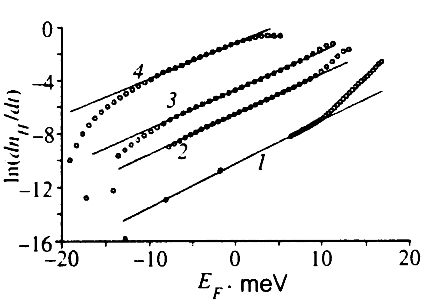

FIG. 4. The same under a pressure of 8 kbar: *1*) 71.4 K, *2*) 78.0 K, *3*) 81.7 K, *4*) 90.0 K.

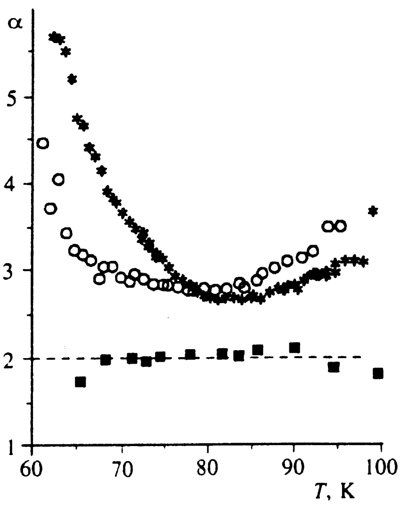

FIG. 5. Values of the coefficient α as a function of temperature for various pressures; α/kT is the slope of the linear portion of the functions in Figs. 2–4. Each point corresponds to a single relaxation curve. *—1 bar, ○—4 kbar, ■—8 kbar.

creases appreciably within the relaxation time, which determines the strong nonexponential character of the process.

The coefficient α in Eq. (1) reflects the charge of the *DX* center, and accordingly that of the "barrier" state.[14] For negatively charged *DX* centers (DX^-), when two electrons are trapped on a single donor level, $\alpha=2$. The exponential term in (1) corresponds to equilibrium filling of the two-electron donor state for the case of B statistics. For a neutral *DX* center (DX^0), $\alpha=1$. The factor N_D^+ in (1) changes within a relaxation time, although considerably more slowly than the exponent. Therefore, the slope of the linear portion of the dependence $\ln(dn_H/dt)\propto E_F$ should be close to the value α/kT. This makes it possible to determine the coefficient α experimentally.

Values of α found at various temperatures are shown in Fig. 5 (each point corresponds to a single relaxation curve). At a pressure of 8 kbar, $\alpha\gtrsim 2$ for all T. When $P=1$ bar and $P=4$ kbar, the value of α turns out to be larger; in both cases there exists a range of T in which $\alpha=2.9\pm0.2$. We recall that at $P=8$ kbar, relaxation of a nondegenerate electron gas is observed, while at $P\leqslant 4$ kbar it is a degenerate electron gas that relaxes.

In order to explain the difference in values of α, let us consider how α is affected by broadening of the relaxation energy barrier, which may be due, e.g., to fluctuations in the Al content of the sample. In the kinetic equation (1), broadening may be introduced by assuming a distribution of the density of "barrier" states with respect to energy[11]:

$$dn^+_{DX}(E)/dt=-\kappa n^+_{DX}(E)\times\exp[-(E_B-\alpha E_F)/kT]. \qquad (2)$$

Here, $n^+_{DX}+(E)$ is the density of "barrier" states at energy E. Each "barrier" state corresponds to a single specific donor atom. $n^+_{DX}(E)$ evolves nonuniformly with time because relaxation occurs primarily through states that are lowest in energy; the relaxation will occur roughly once through each particular "barrier" (donor) state. Integration of Eq. (2) gives the relaxation rate dn/dt.

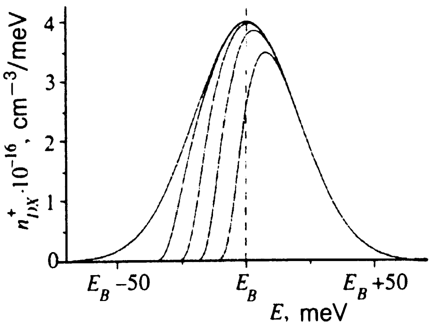

FIG. 6. Evolution of a model density of "barrier" states in the process of relaxation. The shape of the barrier is described by a Gaussian distribution $n(E)=(N_d/\sqrt{2\pi}\Delta)\exp[-(E-E_B)^2/2\Delta^2]$ at the initial time, where $N_d=2\cdot 10^{18}$ cm^{-3} and $\Delta=20$ meV. The curves (from left to right) correspond to values of the parameter $n^+_{DX}(E_0,t)/n^-_{DX}(E_0,t)$ (for $E_0=E_B-10$ meV) of 1.0, 0.99, 0.9, 0.5, and 0.005 respectively.

It is impossible to solve Eq. (2) analytically, because E_F is time-varying. However, (2) does allow a certain simplification. Assume we have a certain fixed value of the energy E_0. Let $n^+_{DX}(E,t_0)$ be the density of "barrier" states at the initial time t_0. Then from Eq. (2) it follows that

$$n^+_{DX}(E,t)/n^+_{DX}(E,t_0)=[n^+_{DX}(E_0,t)/n^+_{DX}(E_0,t_0)]\exp(-(E-E_0)/kT). \qquad (3)$$

This implies that the evolution of $n^+_{DX}(E)$ is determined by its form at time t_0 and temperature, while the position of the Fermi level affects only the rate of that evolution, not its form. We call the reader's attention to the fact that Eq. (3) implies a very strong dependence on energy.

In Fig. 6 we show a model example of such an evolution. The initial distribution $n^+_{DX}(E,t_0)$ is Gaussian here, which is reasonable for the case of *DX* centers if the width of the relaxation barrier is associated with fluctuations in the Al content of the sample. We can in practice include the shift of the left boundary of the distribution $n^+_{DX}(E)$ as an additional effective dependence of the barrier height E_B on the Fermi energy. To each value of E_F there corresponds a new effective height E_B, which depends weakly on temperature for a given E_F; therefore, the thermally activated character of the relaxation is not disrupted.

Numerical calculations using Eqs. (2) and (3), and the model of the evolution of the barrier shape (Fig. 6), show that for degenerate electrons the dependence of E_B on E_F should be very close to linear, as before. The relaxation equation (1) retains its form, but with an increased value of α: for DX^-, $\alpha=2+\delta$, while for DX^0 $\alpha=1+\delta$. In order of magnitude, Δ equals the ratio of the width of the barrier ΔE_B to the maximum value of the Fermi energy. Estimates of this ratio give values of no more than 0.6 to 0.8; the value of α found from experiment, i.e., in the limits 2.9 ±0.2, suggests the representation DX^-, but not DX^0. Judging by all the evidence, only this range of values of α corresponds to a single relaxation process; when α goes outside these limits, we have more than one process. Values of α that are too large at low temperatures are associated with the fact that we cannot distinguish two different relaxation processes in this state, while at large T we cannot distinguish the processes of capture and emission.

Broadening of the barrier should have a much weaker effect on the relaxation of nondegenerate electrons. Actually, whereas the evolution of the barrier shape reflects an absolute change in the concentration of metastable electrons, the coefficient α reflects a shift of their Fermi level. However, for nondegenerate electrons, this shift in the Fermi level is responsible for a much smaller change in n_H and, consequently, a much smaller change in the density of "barrier" states. In other words, the entire relaxation takes place through barriers with the same height: the contribution of barrier broadening (i.e., the correction δ) is found to be negligibly small, and values of the coefficient $\alpha=2$ found at $P=8$ kbar are in good agreement with the picture of capture of nondegenerate electrons by a DX^- center.

Thus, the experiment shows that the rate of relaxation of persistent photoconductivity depends exponentially on the Fermi energy of the metastable electrons: $dn_H/dt \propto \exp(\alpha E_F/kT)$, where $\alpha=2$ for nondegenerate electron gas and $\alpha=2+\delta$ for a degenerate electron gas in the same sample; the number 2 is due to the negatively charged state of the DX center, while Δ reflects the broadening of the thermally activated barrier. The reason for the nonexponential nature of the process is the change in the effective barrier height within a relaxation time.

In speaking of the charge state of the DX center we should, of course, keep in mind that this method of determining it resembles several indirect methods. Although these results are an indication that the DX center is negatively charged, which agrees with the results of investigations by other methods, it is not a conclusive proof.

3.2. Thermally activated relaxation barrier. Criterion for applicability of the kinetic equation

The usual method for finding the height of a thermally activated barrier for an exponential process is to construct an Arrhenius plot of the relaxation time, i.e., τ versus $1/T$. In our case, the nonexponential character renders the concept of a relaxation time meaningless.

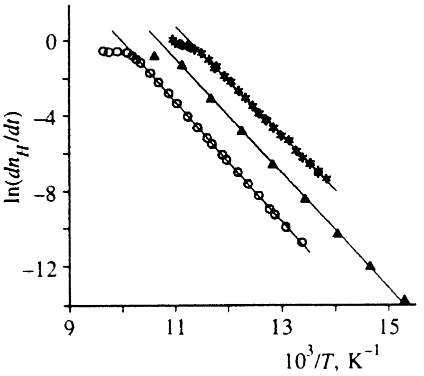

FIG. 7. Examples of Arrhenius plots constructed for electron relaxation rates dn_H/dt at fixed values of the F energy: *—$P=1$ bar, $E_F=60$ meV; ○—$P=4$ kbar, $E_F=18$ meV; ▲—$P=8$ kbar, $E_F=0$ meV.

Therefore, we chose the following approach. Let us pick some value of E_F, and take points that correspond to this choice from an isothermal experimental dependence of dn_H/dt on E_F. We then construct the Arrhenius plot using these points, $\ln(dn_H/dt)$ versus $1/T$. If it is correct to assume that the relaxation is thermally activated in character, then the slope of the plot should be the physical value of E_B^*, i.e., the effective height of the thermally activated barrier corresponding to this Fermi energy for the electron gas. This procedure can be carried out for various E_F, thereby giving the experimental dependence of E_B^* on E_F, which should correspond to $E_B^* = E_B - \alpha E_F$ when the kinetic equations (1) and (2) are applicable.

Figure 7 shows examples of Arrhenius plots constructed in this way for various E_F and P. The plots are linear over a wide range of the relaxation rate. This shows that the process has a thermally activated character, and that the concept of an effective barrier can be applied to it for a given F energy.

In Fig. 8 we show the values of E_B^* obtained as a function of E_F for pressures of 1 bar and 4 kbar. It is clear that E_B^* can change by as much as 100 meV; in the range of

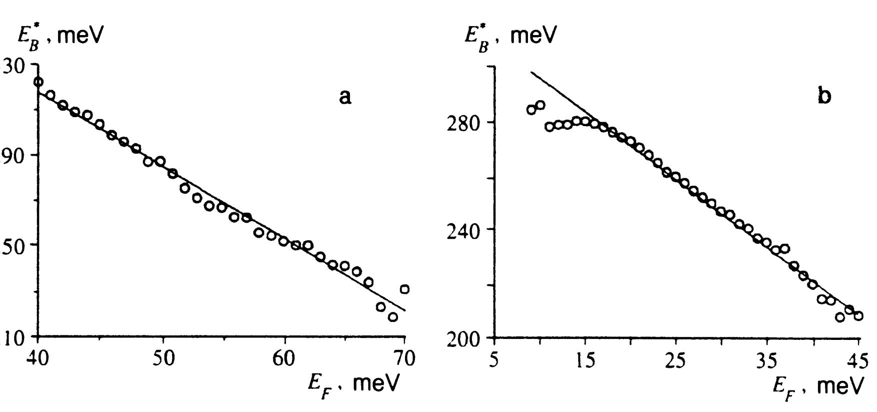

FIG. 8. Values of the barrier for relaxation E_B^* found as a function of the Fermi energy of the electrons: (a) $P=1$ bar, $dE_B^*/dE_F=-3.2$; (b) $P=4$ kbar, $dE_B^*/dE_F = -2.5$.

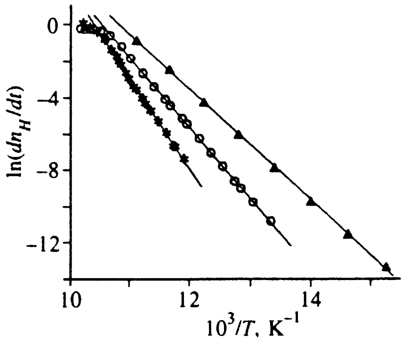

FIG. 9. Examples of Arrhenius plots for electron relaxation rates dn_H/dt constructed for fixed values of the ratio of the Fermi energy to temperature E_F/kT. *—$P=1$ bar, $E_F/kT=6.25$; ○—$P=4$ kbar, $E_F/kT=2.75$; ▲—$P=8$ kbar, $E_F/kT=0.25$.

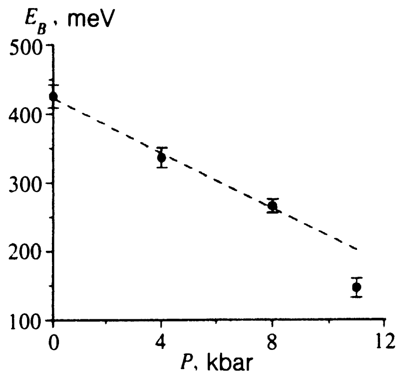

FIG. 11. Height of the relaxation barrier measured from the bottom of the conduction band as a function of applied pressure.

characteristic temperatures for the relaxation $kT \sim 5$–10 meV; this leads to a very strong nonexponential behavior of the rate. The functions $E_B^*(E_F)$ are linear to good accuracy; their slopes $-dE_B^*/dE_F$ (3.2 when $P=1$ bar and 2.5 when $P=4$ kbar) are close to the values of the coefficient $\alpha=2.9\pm0.2$ found above, but do not coincide with them. It is probable that the rather small difference reflects peculiarities of the kinetic process that we did not include.

Another method of constructing an Arrhenius plot is to specify that at each relaxation curve we take the value of dn_H/dt for fixed values of E_F/kT. In this case the slope of the Arrhenius plot should give the height of the barrier E_B measured from the bottom of the conduction band. In contrast to the effective height E_B^*, the value E_B has one well-determined value, which does not depend on the parameter E_F/kT. Therefore, constancy of the value E_B so obtained for various E_F/kT (at fixed pressure) can serve as a criterion for applicability of the kinetic Eqs. (1) and (2), and of our entire approach.

The Arrhenius plots obtained using this method of construction are shown in Fig. 9. It is clear that they are linear to good accuracy. In Fig. 10 we show the height of the barrier E_B obtained from the Arrhenius plot for various pressures and values of the parameter E_F/kT (the specific value of this parameter does not have any special meaning in itself). It is clear that for a given P, E_B is independent of the parameter E_F/kT to an accuracy of 3 to 4%; this rather small deviation could be random in origin. Furthermore, the values of E_B we find coincide within limits of errors with the extrapolation of $E_B^*(E_F)$ to $E_F=0$.

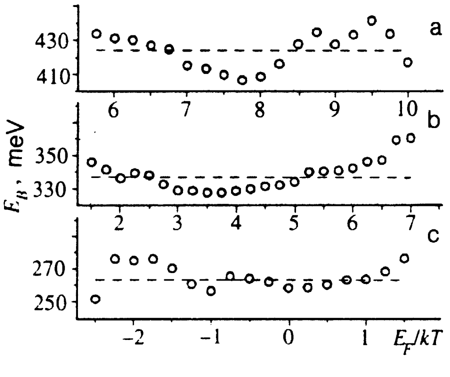

FIG. 10. Height of the relaxation barrier E_B found from the slope of Arrhenius plots (Fig. 9) constructed at fixed values of the parameter E_F/kT as a function of the value of this parameter. (a) $P=1$ bar, (b) $P=4$ kbar, (c) 8 kbar.

The constancy of E_B for various values of the parameter E_F/kT indicate that the kinetic equation (1) can be used to describe capture of electrons by DX centers. Note that until now there have been no reports in the literature regarding experimental criteria for determining whether this description of the relaxation of persistent photoconductivity is adequate.

Figure 11 shows the dependence of the height of the thermally activated barrier E_B on applied pressure. The dependence is found to be very strong: the derivative dE_B/dP is ~ -20 meV/kbar, which greatly exceeds the rate of change of other characteristic energies in the conduction band, the largest of which—the rate at which the Γ and X values approach one another—is almost two times smaller (11–12 meV/kbar).[16] There is a natural explanation for this result: if the center is a DX^-, the barrier height E_B should be computed for two electrons.

Previous values of dE_B/dP reported in the literature differ greatly: from -17 meV/kbar (Ref. 14), which is close to our result, to values an order of magnitude smaller.[7,8] The occurrence of this scatter in the data is not surprising, since the resulting height of the (effective) barrier can vary over very wide limits when the accuracy of the data processing methods is inadequate.

Thus, our new method of determining the height of the thermally activated barrier allows us to determine both the value of the effective barrier as a function of the Fermi energy and its absolute height measured from the bottom of the conduction band for the case of a nonexponential relaxation process. At the same time, we have found a criterion that allows us to decide whether our approach is adequate and whether the kinetic equations are applicable. We have shown that the change in the barrier height under pressure exceeds by a factor of two the rate of convergence

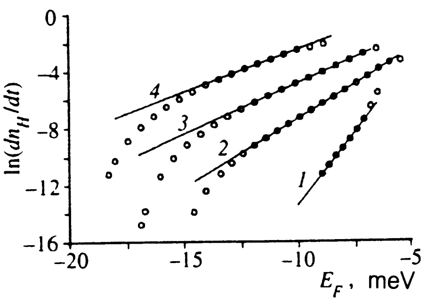

FIG. 12. Examples of dependence of the electron relaxation rate dn_H/dt (on a logarithmic scale) on the Fermi energy of the electron gas under a pressure of 11.5 bar at various temperatures *1*—59.6 K, *2*—67.3 K, *3*—72.0 K, *4*—76.8 K.

of the Γ and X valleys, which can be explained within the framework of a picture involving negatively charged DX centers.

3.3. Relaxation of activated persistent photoconductivity

We attempted to use our approach to describe the relaxation of the activated type of persistent photoconductivity.[17] In a sample under a pressure $P=11$ kbar, both the DX level and the donor level X^* belong to the X valley, which is located below the bottom of the Γ valley in energy. Illuminating the sample leads to metastable filling of the X^* level (in this case, no conductivity is observed at 4.2 K). As the temperature increases, electrons from the X^* level are thermally activated into the Γ valley, and simultaneously relax into a state of the DX center.

We found that the relaxation process for activated persistent photoconductivity differs considerably from that observed at lower pressures. Figure 12 shows plotted examples (on a logarithmic scale) of the dependences of the relaxation rate for electrons dn_H/dt on their Fermi energy at constant temperature. On these curves, we observe a linear portion as before; however, its slope turns out to be very large, implying a value of the coefficient α that lies between 4 and 15, which clearly has no physical content. Furthermore, when we constructed Arrhenius plots for dn_H/dt at fixed values of E_F/kT, the barrier height E_B we found varied within the range 100 to 250 meV for various values of E_F/kT, which naturally is physically meaningless. Consequently, this criterion indicates that the kinetic equation (1) cannot be used to describe the relaxation in this case.

For the case of activated persistent photoconductivity, the Hall concentration n_H is only a small part of the overall concentration of metastable electrons, the majority of which are localized at the donor level X^*. If we start from the general picture of thermally activated relaxation through an energy barrier, we can expect that an additional preexponential factor will appear in the kinetic equation (1); however, the exponent retains its form, with a coefficient $\alpha\sim 2$. From our results, however, it follows that the kinetic equation can change its form in a more fundamental way.

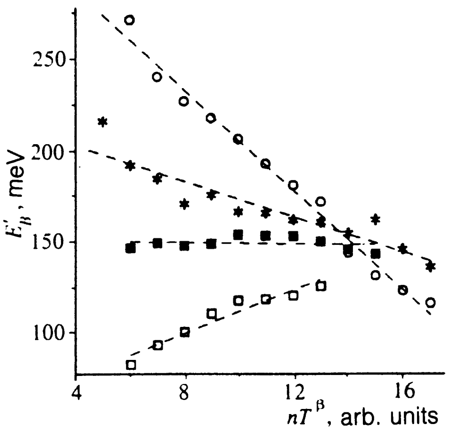

FIG. 13. "Relaxation barrier height" E'_B found through various methods of constructing Arrhenius plots for dn_H/dt. The value of dn_H/dt was taken for fixed values of the parameter nT^β: ○—$n/T^{3/2}$, *—n, ■—$nT^{1/2}$, □—nT.

A more general form of the equation for thermally activated relaxation can be written as follows:

$$dn_H/dt=\kappa F\exp(-E_B/kT+G), \tag{4}$$

where F and G are functions of the parameters of the electron gas, i.e., its concentration, temperature, etc. The preexponential function F has only a weak influence on the accuracy to which E_B is determined. Therefore, in order to find the barrier height E_B it is necessary to construct Arrhenius plots for dn_H/dt at fixed values of the function G. Previously we set $G=\alpha E_F/kT$.

We made an attempt to find some combination of n and T that could serve as the argument of the function G. Constancy of the barrier height E_B for various values of this argument could be used as such a criterion, and Fig. 13 shows the results of using it in this way. The "barrier height" is found from the slope of the (linear) Arrhenius plots, which are plotted at fixed values of the argument nT^β; this was done several times for various values of β. For nondegenerate electrons the condition $E_F/kT=\text{const}$ used previously is equivalent to $n/T^{3/2}=\text{const}$ ($\beta=-3/2$).

It is clear from Fig. 13 that the "barrier height" is unchanged if the Arrhenius plot for dn_H/dt is constructed at fixed values of $nT^{1/2}$, i.e., this product can be a suitable argument for the function G. The results of this plotting procedure differ markedly from the results of plotting these curves for fixed values of, say, n or nT. The "barrier height" (determined under the condition $nT^{1/2}=\text{const}$) is ~ 150 meV, which is smaller than the value found by extrapolating the function $E_B(P)$ (~ 200 meV, Fig. 11); however, the agreement may be considered satisfactory.

Figure 13 shows that the choice of the argument of the function G has a very strong influence on the resulting value of the "barrier height". Therefore, if a function of the argument $nT^{1/2}$ appears in the kinetic equation (2), it will also appear in the exponent, although not in the preexponential factor. The origin of the additional term in the exponent remains unclear within the kinetic equation.

Most of the assertions in this section are tentative. As a conclusion we can state that the kinetic equation, which adequately describes relaxation of the usual persistent photoconductivity, loses its usefulness for the case of persistent photoconductivity of activated type.

4. CONCLUSION

We have thus carried out a detailed investigation of the (nonexponential) relaxation of persistent photoconductivity in AlGaAs:Te. We have shown experimentally that it is thermally activated in nature. The reason for its nonexponential behavior is the dependence of the height of the effective energy barrier for relaxation on the Fermi energy of the electron gas. This dependence reflects the charge state of the *DX* center and broadening of the barrier. We have developed a method for correctly determining the barrier height, which is at the same time a criterion for applicability of a kinetic relaxation equation of specific form. We found that the relaxation barrier measured from the bottom of the conduction band depends strongly on pressure. Its rate of decrease is roughly double the shift of the Γ valley under pressure.

The results of this paper indicate a negative charge state for the *DX* center.

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[1] R. J. Nelson, Appl. Phys. Lett. **31**, 351 (1977).
[2] P. M. Mooney, J. Appl. Phys. **67**, R1 (1990).
[3] D. V. Lang, R. A. Logan, and M. Jaros, Phys. Rev. B **19**, 1015 (1979).
[4] T. N. Morgan, Phys. Rev. B **34**, 2664 (1986).
[5] D. V. Lang, J. Appl. Phys. **45**, 3023 (1974).
[6] P. M. Mooney, E. Calleja, S. I. Wright, and M. Heiblum, in *Defects in Semiconductors*, H. J. von Bardeleben (ed.), Mater. Sci. Forum (1986), vol. 10–12, p. 417.
[7] M. F. Li, W. Shan, P. Y. Yu *et al.*, Appl. Phys. Lett. **53**, 1195 (1988).
[8] W. Shan, P. Y. Yu, M. F. Li *et al.*, Phys. Rev. B **40**, 7831 (1989).
[9] H. J. Queisser and D. E. Theodorou, Phys. Rev. B **33**, 4027 (1986).
[10] N. S. Caswell, P. M. Mooney, S. L. Wright, and P. M. Solomon, Appl. Phys. Lett. **48**, 1093 (1986).
[11] P. M. Mooney, S. L. Wright, and N. S. Caswell, J. Appl. Phys. **62**, 4786 (1987).
[12] I. Izpura and E. Muñoz, Appl. Phys. Lett. **55**, 1732 (1989).
[13] V. Mosser, S. Contreras, R. Piotrzkowski *et al.*, Semicond. Sci. Technol. **6**, 606 (1991).
[14] V. Mosser, S. Contreras, J. L. Robert *et al.*, Phys. Rev. Lett. **66**, 1737 (1991).
[15] I. E. Itskevich and V. D. Kulakovskii, Semicond. Sci. Technol. **6**, B62 (1991).
[16] N. Lifshits, A. Jayaraman, R. A. Logan, and H. C. Card, Phys. Rev. B **21**, 670 (1980).
[17] I. E. Itskevich and V. D. Kulakovskii, Zh. Eksp. Teor. Fiz. **94**(6), 219 (1988) [Sov. Phys. JETP **67**, 1210 (1988)].
[18] D. J. Chadi and K. J. Chang, Phys. Rev. B **39**, 10063 (1989).
[19] M. Baj, L. Dmowski, and T. Slupinski, Phys. Rev. Lett. **71**, 3529 (1993).
[20] L. Dobaczewski and P. Kaczor, Phys. Rev. Lett. **68**, 66 (1991); Phys. Rev. B **44**, 8621 (1991).
[21] W. Jantsch, Z. Wilamowski, and G. Ostermayer, Semicond. Sci. Technol. **6**, B47 (1991).
[22] J. A. Wolk, M. B. Kruger, J. N. Heyman *et al.* Phys. Rev. Lett. **66**, 774 (1991).
[23] E. S. Itskevich, Pribor. Tekh. Eksp. **4**, 148 (1963).
[24] E. S. Itskevich, A. N. Voronovski, A. F. Gavrilov, and V. A. Sukhoparov, Pribor. Tekh. Eksp. **6**, 161 (1966).
[25] E. F. Schubert, J. Knecht, and K. Ploog, J. Phys. C **18**, L215 (1985).
[26] T. N. Theis and S. L. Wright, Appl. Phys. Lett. **48**, 1374 (1986).

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