interaction, thus proving the existence of explosive instability[1]).

In the absence of linear dissipation (i.e., when the additional resistances are disconnected), the amplitudes of the waves ω_1 and $\omega_2 = 2\omega_1$ were constant along the line if the synchronism conditions were not satisfied. The behavior of the amplitudes of these waves in the case of complete synchronism is shown in Fig. 2. The simultaneous growth of the waves, which demonstrates the explosive character of the nonlinear interaction, is analogous to the growth of the amplitudes of coupled waves with energies of opposite signs in a non-equilibrium plasma.

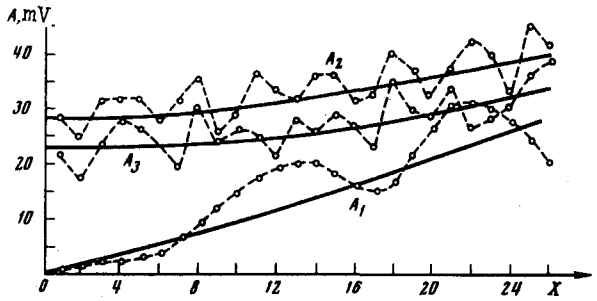

Fig. 3

Figure 3 shows the results of an investigation of the non-degenerate process in a system where the linear dissipation is small. We see that in the presence of two waves there is produced a third wave of combination frequency, generation of which is accompanied by the growth of all three waves (when one wave propagated in this system, its amplitude decreased slowly).

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BREAKDOWN AND RECOMBINATION KINETICS CONNECTED WITH THE EXCITED STATES OF A SHALLOW DONOR IN n-Ga

Yu.A. Astrov and A.A. Kastal'skii
A.F. Ioffe Physico-technical Institute, USSR Academy of Sciences
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We report here the results of an investigation of the kinetics of impurity breakdown and recombination, connected with the first and higher excited states of a shallow donor in n-Ge. Simultaneous registration of the current-voltage characteristics leads to the conclusion that an appreciable contribution is made by impact ionization of the excited states to the total intensity of the breakdown process.

[1]) The spatial beats are connected with the presence of weak reflected waves.

EXPERIMENT

The investigations were performed in the temperature interval 2.5 - 4.2°K. A voltage $E_{=}$ (in the form of pulses of 10 μsec duration) and short microwave pulses (10 - 100 nsec with fronts of 4 - 5 nsec), with electric field vector $E_{\sim} \parallel [100]$ were applied to n-Ge samples oriented along the [100] axis[1]. Such a procedure makes it possible to decouple electrically the excitation and the registration circuits. The condition $E_{\sim} \ll E_{=}$ was maintained. We chose for the measurements samples with $N_D = 5 \times 10^{12}$ cm^{-3} ($N_A \simeq 2 \times 10^{12}$ cm^{-3}), $N_D = 2 \times 10^{13}$ cm^{-3} ($N_A \simeq (5 - 6) \times 10^{12}$ cm^{-3}), and $N_D = 1 \times 10^{14}$ cm^{-3} ($N_A \simeq 2 \times 10^{13}$ cm^{-3}). The sample length was 6 mm (the waveguide width was 4 mm).

Figure 1 shows typical breakdown and relaxation oscillograms, obtained under the simultaneous action of the dc field $E_{=}$, which ensured breakdown, and the microwave pulse. It is seen, first of all, that the kinetics of the rise and fall of the current has a complicated structure that varies with the field $E_{=}$. The rise of the current has a clearly pronounced kink. The short first segment (I) at T = 4.2°K is not time-resolved by our apparatus, and its amplitude increases with increasing $E_{=}$. The slope of segment II varies non-monotonically with the field $E_{=}$, the rise being followed by a fall to almost zero value.

The relaxation to the initial state also contains two components (segments III and IV), and the start of the fast segment III and the termination of the slower segment IV are exponential. The behavior in the region of the kink of the curve is more complicated. When the field $E_{=}$ increases, the role of segments I and III in the overall kinetics becomes predominant (Fig. 1, a - e, j, k).

At high values of $E_{=}$ the kinetics is made complicated by spikes of varying polarity, occurring when the microwave pulses are turned on and off (Figs. 1d

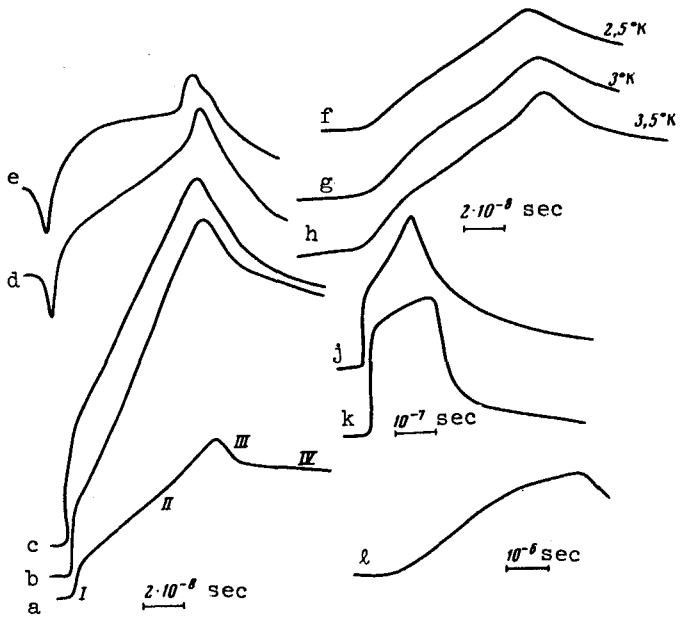

Fig. 1. Typical oscillograms of conductivity variations: a - e, j - ℓ) T = 4.2°K, $E_{=}$(V/cm): a) 18, b) 18.6, c) 19.3, d) 27, e) 30, j) 20, k) 25, ℓ) 18.6 T, °K: f) 2.5, g) 3, h) 3.3; $E_{=}$ = 17.6 V/cm.

[1]The [100] direction, which is symmetrical with respect to the valleys, was chosen to avoid intervalley redistribution of the electrons, which would greatly complicate the breakdown picture [1].

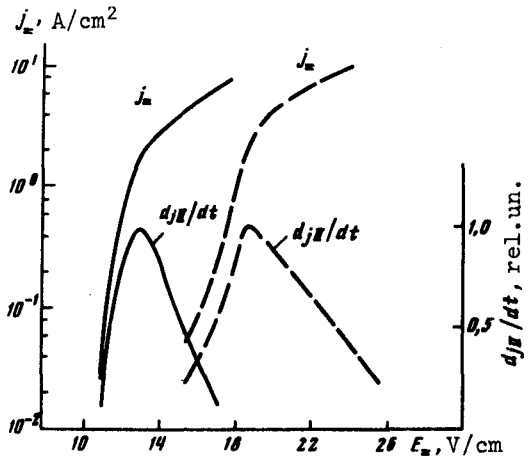

Fig. 2

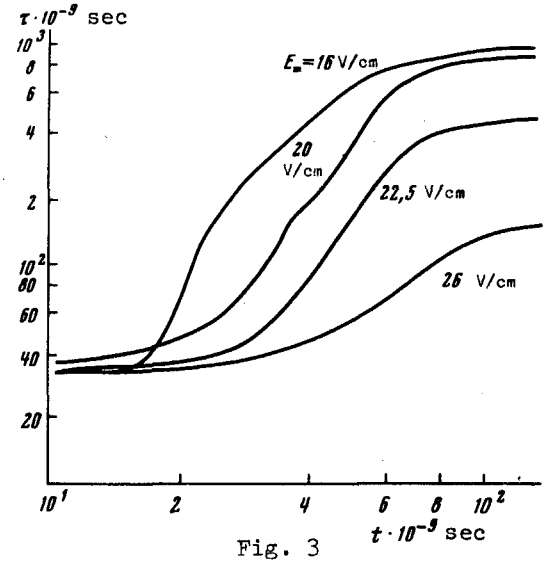

Fig. 3

Fig. 2. Current-voltage characteristics $j_=(E_=)$ and plots of $dj_{II}/dt = f(E_=)$ for samples with different concentrations N_D. T = 4.2°K. Continuous lines - $N_D = 10^{14}$ cm^{-3}, dashed lines - $N_D = 2 \times 10^{13}$ cm^{-3}.
Fig. 3. Plots of $\tau(t)$ at $N_D = 5 \times 10^{12}$ cm^{-3} and T = 4.2°K.

and e) and connected with the change in the carrier mobility. For all the investigated samples, the current pulses had approximately the same shape and differed only in the dependence of the different segments on the electric fields (for the pure samples (5×10^{12} cm^{-3}, 2×10^{13} cm^{-3}), the changes indicated above occur in a wider range of $E_=$. Figures 1f - 1h show pulse oscillograms for the same constant field and different temperatures, for samples with $N_D = 2 \times 10^{13}$ cm^{-3}. We see that the slope of I depends strongly on the temperature. At $E_=$ = 18 V/cm and T = 2.5°K, there is no slope at all, whereas at T = 4.2°K and at the same electron concentration in the band it is already appreciable (Fig. 1b). With increasing field, segment I appears also at T = 2.5°K and its amplitude increases with increasing $E_=$. At this temperature, the duration τ_I exceeds the rise time of the microwave pulse and is equal to ~10 - 12 nsec.

The second segment of the growth curve varies little with temperature, but depends strongly on the field $E_=$ (Figs. 1a - e). We see further that if there is no segment I (Fig. 1f), there is likewise no relaxation component III. If we recognize further that in strong fields the curves consist mainly of only segments I and II (Fig. 1k), then we can conclude that the times τ_I and τ_{III} (and accordingly τ_{II} and τ_{IV}) are determined by opposing processes pertaining to the same donor level.

Figure 2 shows plots of the slope dj_{II}/dt of segment II against $E_=$ and the current-voltage characteristics $j_=(E_=)$ for samples with $N_D = 2 \times 10^{13}$ cm^{-3} and 1×10^{14} cm^{-3}, from which it follows that the slowing down of the growth of the breakdown current at high voltage occurs precisely when dj_{II}/dt begins to decrease. For all samples, the relaxation of the current to the initial state occurred in identical fashion: the amplitude of segment III increased with increasing field, the time τ_{III} changing insignificantly, whereas the amplitude

of segment IV and the fall-off time τ_{IV} decreased appreciably. Figure 3 shows families of curves for the instantaneous relaxation time $\tau = n(t)/(dn/dt)$ at different intensities $E_=$ for samples with $N_D = 5 \times 10^{12}$ cm^{-3} at T = 4.2°K. The figures reveal the presence of two characteristic segments corresponding to τ = const. These values were taken to be the exponential-relaxation parameters τ_{III} and τ_{IV}. The time τ_{IV} decreases noticeably with increasing $E_=$ ($\tau_{IV}(E_= = 16$ V/cm)/$\tau_{IV}(E_= = 26$ V/cm) ≃ 10).

DISCUSSION OF RESULTS

The obtained data indicate that segments I and II differ in their nature. First of all, the sharp temperature dependence of the amplitude of segment I points to a thermal rather than impact ionization mechanism. The decrease in the rate of capture by the donors when the carriers are heated by the microwave pulse upsets the equilibrium between the ionization and the recombination in favor of the thermal mechanism. The high rate of current growth in this segment ($\lesssim 5 \times 10^{-9}$ sec at T = 4.2°K) indicates that this process is determined only by the second excited state (third donor level), since the deeper levels cannot ensure such a high rate of thermal ionization [3]. At T = 2.5°K, the appearance of the segment I with increasing field is due to the population of this state and the enhancement of the thermal ionization. The weakness of the thermal ionization at T = 2.5°K ($\tau_I \simeq 10 - 12$ nsec) indicates that the high-lying states are likewise not responsible for segment I.

Segment II is patently connected with the impact mechanism of ionization, since it depends little on the temperature and varies strongly with the field. It is typical that at T = 2.5°K, when there is no segment I (Fig. 1f), owing to the small population of the level 3, the slope of segment II is the same as at T = 4.2°K. This indicates that the impact ionization of level 3 makes a negligible contribution to segments of type II.

Further choice between levels 1 and 2 is facilitated by the fact that with increasing $E_=$ the slope of segment II decreases at concentrations n that are clearly lower than the initial concentration $N_D - N_A$. Figure 2 shows the sharp drop in the slope of segment II at $n \simeq 4 \times 10^{12}$ cm^{-3} for $N_D = 10^{14}$ cm^{-3} and at $n = 2 \times 10^{12}$ cm^{-3} for $N_D = 2 \times 10^{13}$ cm^{-3}. Thus, we arrive at the conclusion that the slope of II is determined by impact ionization of the level 2. The ionization times of the ground state of I are much larger (Fig. 1ℓ). The decreased slope of dj_{II}/dt can be attributed to the depletion of the level 2 as a result of the impact ionization, the intensity of which increases with increasing n. This increases the number of empty centers, and consequently enhances the recombination process, leading in turn to a slowing down of the breakdown and to a decrease in the slope of the current-voltage characteristic.

It is natural to conclude on the basis of this model that the recombination is connected with the same levels 2 and 3 as the ionization: the fast relaxation τ_{III} is determined by capture by the level 3, and the time τ_{IV} determines the transition to the first excited state 2. It is characteristic that the time τ_{IV} decreases with increasing field, regardless of the decrease in the electron capture cross section with the field [4]. The reason may be that at the concentrations registered by us the depletion of the donors by impact ionization influences the recombination rate more effectively than the decrease of the cross section.

We thus arrive at the conclusion that the observed kinetics is wholly connected with the first and second excited states of the donor, which play a

major role in the development of the breakdown.

The authors are grateful to S.I. Kokhanovskii and Yu.S. Lelikov for help with the experiment.

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POSITRONS IN CRYSTALS WITH DEFECTS

A.D. Kokrushin and I.I. Bardyshev
Institute of Chemical Physics, USSR Academy of Sciences
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It is known that defects play an important role in the properties of a real crystal. Useful information on the microscopic properties of point defects of a crystal lattice can be obtained by the positron-annihilation method. The positive charge of the positron enables it to be captured by a cation vacancy to form the so-called A-center (Brandt's model [1]). The interaction of a positron with an F center can lead to the production of a positronium-like bound state in an anion vacancy.

Experimental investigations of the positron lifetimes in ionic crystals with defects have revealed the presence of long-lived components $\tau_2 \sim 0.5$ nsec and $\tau_3 \sim 1$ nsec, corresponding to annihilation of positrons captured by cation vacancies in F centers [2 - 6]. The intensities I_2 and I_3 of the long-lived components are determined by the concentrations of the corresponding defects. The presence of defects in the crystal causes also a narrowing of the curves of the angular correlation of the annihilation γ quanta [7, 8].

It must be noted that most studies were made on alkali-halide crystals, in which the relative concentration of the cation vacancies, estimated from the annihilation characteristics, did not exceed 10^{-5}. Yet to explain the positron-capture mechanism it is important to investigate crystals whose cation vacancy concentration is known beforehand and can be varied over a wide range.

We have investigated $Fe_{1-x}S$ crystals of stoichiometric (x = 0, sample 1) and non-stoichiometric composition (sample 2). The samples were prepared by the "ceramic" method described in [9]. The sample control was by measuring the spectra of the nuclear γ resonance and x-ray diffraction. The NGR spectrum of sample 1 revealed a simple structure of six hyperfine components, which is evidence of the stoichiometric composition of the sample [10]. The spectrum of sample 2 revealed a complicated structure consisting of a superposition of several sextuplets, thus evidencing a shortage of iron ions in the crystal lattice [10]. An analysis of the x-ray diffraction patterns has made it possible to determine quantitatively the concentration of the cation vacancies in sample 2, which turned out to equal $n_v = (2.5 \pm 0.2) \times 10^{21}$ cm^{-3} ($Fe_{0.92}S$).

The positron lifetime was measured by the standard procedure using "Ortec" apparatus with a model-437-A "time-amplitude" converter. The half-width of the peak of the prompt coincidences from Co^{60} was 0.4×10^{-9} sec, and the logarithmic slope of the sides of the peak did not exceed 0.7×10^{-9} sec. The contribution from positron annihilation in the source [11] was subtracted from the experimental spectra. The positron lifetimes were measured at room temperature; the results are given in the table.