PRAMANA
— journal of
physics

Vol. 62, No. 5
May 2004
pp. 1111–1119

Recombination instability and domainisation in p-Ge(Au)

I K KAMILOV, KH O IBRAGIMOV, K M ALIEV and N S ABAKAROVA
Laboratory of Nonlinear Dynamic and Chaos, Institute of Physics, Daghestan Scientific Center of RAS, 367003, 94 M.Yaragskogo St., Makhachkala, Daghestan, Russia
Email: khmurat@iwt.ru

MS received 14 July 2003; accepted 12 December 2003

Abstract. Results of an experimental study of short and long p-Ge(Au) samples are presented and compared qualitatively with data furnished by the one-dimensional theoretical model describing the evolution of domain instability in a two-parametric space 'voltage V-emission coefficient β'. According to the theory, single-, double-, and multi-subdomain states and order–disorder–order transitions via intermittency have been observed in the system with increasing voltage. Three operation regimes of the system are found, depending on the region of the parametric space: ohmic, quenched (pulsing) and transit-time. In short samples, a second portion with S-switching is revealed in the current–voltage characteristic.

Keywords. Conductivity phenomena; noise processes.

PACS Nos 72.20.-i; 72.20.Ht; 72.70.+m

1. Introduction

A one-dimensional theoretical model [1,2] developed for Au-compensated n-Ge has been studied experimentally for the case when recombination instability in high electric fields makes the system unstable and leads to electric current oscillations. The theoretical model takes into account both temporal and spatial evolution of a high electric field domain generated in the system on changing the applied voltage V and the emission coefficient β, i.e., in the 'voltage-emission' parametric space. Depending on a region of the parametric space, the experimental system under study exhibits three different modes of operation (ohmic, quenched and transit-time modes), subdomains are generated, and some new properties are observed, untypical of the common non-linear systems. The same properties may be manifested in the non-linear mode in the case of the Gunn effect [3,4], very important for semiconductor device applications, since the initial equations for both the models are very similar.

The recombination current instability, first reported by Stafeev [5] and Bonch-Bruevich and Kalashnikov [6–8], has been studied in sufficient detail in Au-compensated n-Ge, a typical non-linear system, in the temperature range 16–35 K. This type of instability has been studied in other Ni- and Mn-doped materials [9–14] as well. All these results have been obtained in a linear approximation on a threshold of the recombination instability beginnings.

2. Experimental

We report here the results obtained in certain specially chosen areas of the two-parametric space (β, V) of experimental observation of the recombination current instability in Au-compensated p-Ge and a detailed study of the one-dimensional theoretical model [1,2] in a wide region of the two-parametric space. The experiment was carried out at 77 K in the voltage-controlled mode at pulse duration not exceeding 500 μs. Current–voltage (I–V) characteristics and time series were studied and used to plot phase portraits, bifurcation diagrams and power spectra. The time series of electric current oscillations were digitized by means of an analogue-digital converter with a sampling rate of 200 MHz. The employed automated experimental set-up made it possible to vary gradually and widely the control parameters of the two-parametrical space. Illumination by an ordinary incandescent lamp (100 W) and/or injection of non-equilibrium carriers from contacts were used to change the emission coefficient. Contacts were made of In with 0.5% Ga and Sn with 7% Sb and applied to two opposite edges of the samples to provide good injection of non-equilibrium carriers.

Long ($d = 3/8$ mm) and short ($d = 1/3$ mm) p^+–p–n^+-structures were made of Sb-doped p-Ge compensated with Au. Here, d is the linear length of the studied samples, and the terms 'long sample' or 'short sample' do not mean the generally accepted relationship of d and LD, where LD is the diffusion length. The samples were cut out of the bulk material in the form of 8/3 mm- and 1/3 mm- long rectangular bars with 1-mm^2 cross-section. Two groups of samples have been investigated. First group of samples under study had the following parameters at 77 K: $\rho_1 = 8.7 \cdot 10^4$ Ω·cm, $\mu_1 = 16,500$ cm^2/V·s, $P_{01} = 4.33 \cdot 10^9$ cm^{-3}. Second group of samples at 77 K had next parameters: $\rho_2 = 1.95 \cdot 10^5$ Ω·cm, $\mu_2 = 29,900$ cm^2/V·s, $P_{02} = 1.07 \cdot 10^9$ cm^{-3}, where ρ is the resistivity, μ is the hole mobility, and P_0 is the equilibrium hole concentration.

2.1 *Long samples*

Depending on the emission coefficient, the I–V characteristics of the samples studied were first ohmic or superlinear and then levelled-off or became N-shaped with large current oscillations and current pulse modulation factor as high as 90%. For experiment at the long samples the N-shaped or levelled-off portions of I–V characteristics were chosen. Raising the voltage led to a steep rise in the current or to an S-shaped I–V characteristic.

Figure 1 shows a typical I–V characteristic for the case of optical generation of non-equilibrium carriers. According to the theory [1,2] and experimental data

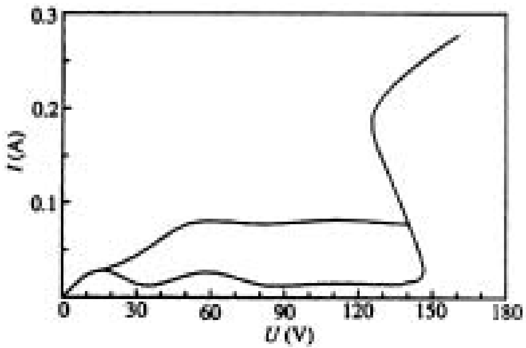

Figure 1. I–V characteristics of the sample at 77 K. Between two lines is the oscillation region.

[6–14], the oscillations generated in the sample can be explained by periodic appearance, motion and disintegration at a contact of a high electric field domain. A study of the field distribution along the sample demonstrated that in p-Ge(Au), in contrast to n-Ge(Au), a high-field domain is always generated at the anode and moves towards the cathode. The electric field strength at the anode was as high as 2.8 kV$\cdot$cm^{-1} at an average field of 300 V$\cdot$cm^{-1} in the sample.

Figure 2 shows time realizations, phase portraits and power spectra for current oscillations in the sample at a given illumination and varied applied voltages that allow comparison with the theoretical model. Figure 2(1) corresponds to the case when the emission coefficient β is large, i.e., the domain cannot maintain its shape, and it stops growing and is quenched before reaching the cathode. Figure 2(2) shows a newly born growing domain, with negative charge building up on the cathode side of the domain and decreasing on its anode side, owing to carriers released from occupied traps. In accordance with the model [1,2], the residual domain starts growing again. The cycle repeats itself and this higher frequency mode is named 'quenched'. However, in our opinion, it should be termed as the 'pulsing' mode, this name better describes the real situation in the sample. Depending on control parameters, the character of motion changes from quenched to transit-time mode in two ways. The first of these is the intermittency, when the amplitude of minor oscillations in the quenched mode slowly increases until a large peak suddenly appears, or when the amplitude of the quenched mode decreases, with the oscillations becoming less regular and large peaks occurring more frequently. In this case, the oscillations of the quenched mode correspond to a laminar phase of the intermittency, and oscillations of the transit-time mode, to a turbulent phase. In the second case, the system suddenly changes the spatial structure of the wave at certain parameters, as shown in figure 2(2). It should be noted that the oscillations of the quenched mode do not manifest themselves at transverse 'Hall probes' formed in the middle of the sample 3 mm away from the cathode and anode. However, any large amplitude peak related to a turbulent burst always arises synchronously with electric current oscillations in the sample. With the applied voltage raised further, the travelling domain grows large enough to reach the cathode and the system exhibits oscillations with frequency determined by the time during which the

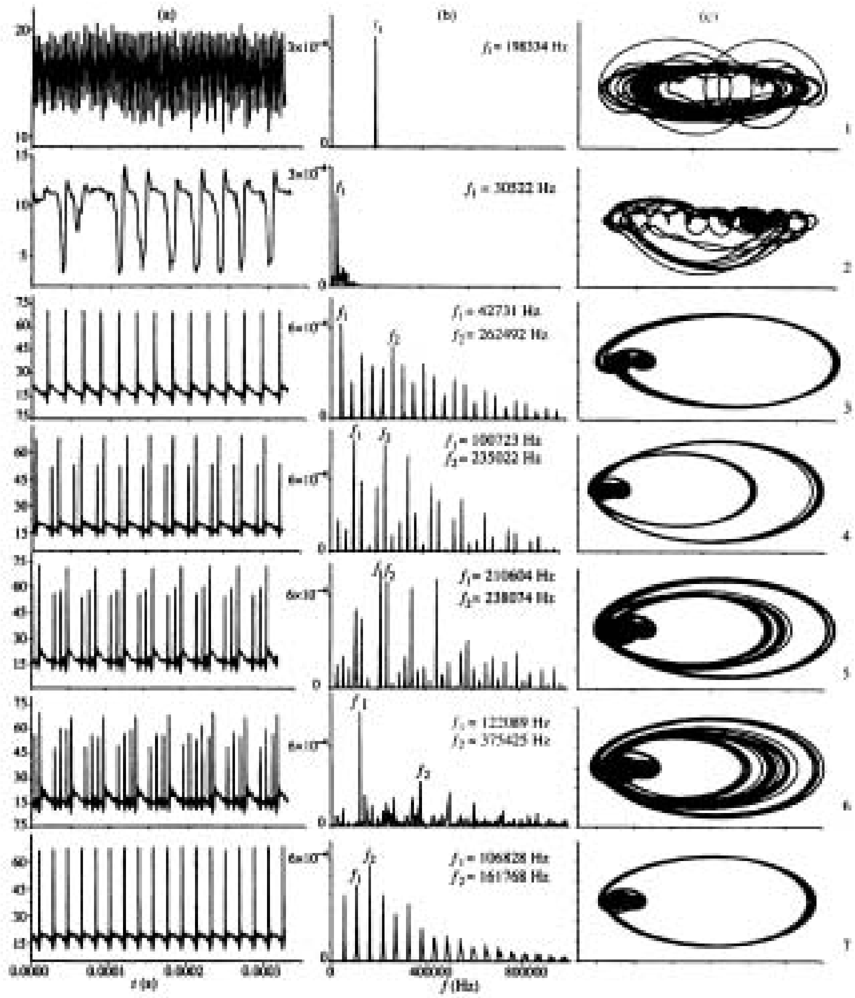

Figure 2. (**a**) Electric current oscillations in the sample, (**b**) their power spectra and (**c**) phase portraits at various applied voltage: (1) 16 V; (2) 20 V; (3) 98 V; (4) 105 V; (5) 120 V; (6) 140 V and (7) 142 V.

travelling domain moves from the anode to the cathode (figure 2(3)). This situation corresponds to the transit-time mode of travelling domains in the theoretical model.

In addition, the model [1,2] predicts generation of sub-domains at certain system parameters. Figures 2(3–6) illustrate generation of 1, 2, 3 and more sub-domains. In this case, the frequency of generation of main domains decreases; the intervals between them are filled with sub-domains, with the noise component in the system simultaneously growing. We experimentally revealed situations when the number of sub-domains was not always constant, even though the parameters of the system were maintained constant during the measurements (figure 2(6)). A further rise in voltage led to an abrupt rearrangement of the system with its self-organization: the single-domain situation occurred in the sample once again (figure 2(7)). In this case, the frequency of the main peak of the newly arising single-domain mode was always greater than that of the preceding single-domain mode. This can be accounted for by a rise in the domain velocity, resulting from an increase in drift velocity on raising the applied voltage. Three order–disorder–order transitions of this kind were observed at a prescribed illumination level over the entire range of applied voltages, to the point of S-switching. At intermediate values of the control parameters, chaotic states corresponding to intermittency were found. These states may be associated with the interaction of different oscillating modes. The sub-domains formation and the related oscillations with periods of 2, 3, 4, 6 and 8 fall beyond the known standard scenarios of transition to a chaotic state (e.g., the Feigenbaum period-doubling scenario [15]) and cannot be described by the known universal operators and constants, characteristic of a common determined chaotic state. However, when the system passes from a chaotic state to self-organization, a reverse cascade of period-doubling bifurcations can be observed in a certain area of the parametric space upon very fine adjustment of the parameters.

The so-called ohmic mode of the model [1,2] was observed in experiment either at a too high level of non-equilibrium carrier generation under illumination/injection or in the case when, at a fixed generation rate, the electric field was not high enough for trapping deep levels to prevail over emission. It follows from an analysis of experimental data that a prescribed mode of the system operation (e.g., two-domain mode) can be maintained over a wide region of the parametric space if the illumination intensity and the strength of the electric field applied to the sample are raised simultaneously. Irregular domain formation was observed in the system before the S-switching (catastrophe), looking more like intermittency in typical determined systems. The lifetime of the domains and their number before switching are hardly controllable in the system under study and are very sensitive to changes in both the electric field and the emission coefficient.

2.2 *Short samples*

A distinctive feature of a current–voltage characteristics obtained for comparatively short samples under illumination and without injection from contacts is a smooth transition from the ohmic to the sublinear portion (figure 3a). This transition is characterized by chaotic oscillations appearing at the beginning of sublinearity and a band of continuous noise (figure 3b), which gives rise to spike oscillations (figure 3c) of the domain type with increasing voltage. Occasionally, these oscillations are periodic and show period doubling (figure 3d), tripling, etc. But for most part of the sublinear portion of I–V characteristics they are chaotic, resembling an intermittency (figure 3e). In this case, the depth of modulation of a pulse with current oscillations reaches 90%, the spectral characteristic is a band of continuous noise, and the I–V characteristic becomes S-shaped with voltage increasing further.

With increasing voltage in the case of simultaneous injection from contacts and exposure of a sample to light, the characteristic exhibits a smooth transition from the linear portion to a superlinear one, with subsequent transitions to a sublinear

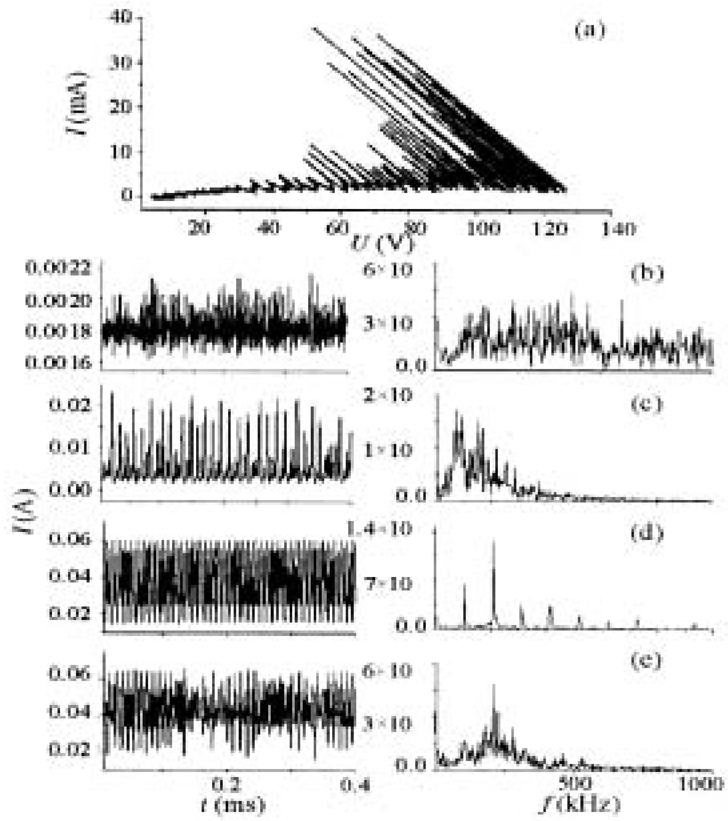

Figure 3. (**a**) I–V characteristic, (**b**)–(**e**) temporal realizations and power spectra at different voltages applied to the sample: (**b**) -25.8 V, (**c**) -36.7 V, (**d**) -47.5 V and (**e**) -56 V.

or N-shaped portion. The beginning of the sublinear portion is characterized by current oscillations similar in shape to coherent oscillations (figure 4a), which pass via quasi-periodicity (figure 4b) to chaotic oscillations (figure 4c) with increasing voltage. Further increase in voltage leads to spike oscillations of the domain type (figure 4d), which exhibit periods of 2, 3 and 4 in some regions of the parametric space and subsequently, prior to S-switching, become chaotic via intermittency. It should be noted that it is difficult to observe in short samples the whole variety of situations related to rearrangement of the spatial structure of a wave and smooth generation of subdomains. However, we can always observe the theoretically predicted operation modes (ohmic, quenched and transit-time) prior to S-switching in the levelled-off or N-shaped portions of I–V characteristics upon a fine selection of regions of the parametric space. In our opinion, the most interesting results have been obtained for type-I samples of $d = 1/3$ mm length with injecting contacts under simultaneous strong irradiation.

Figure 5 shows the evolution of current–voltage characteristics of a sample in the case when the applied voltage is gradually raised at constant illumination intensity.

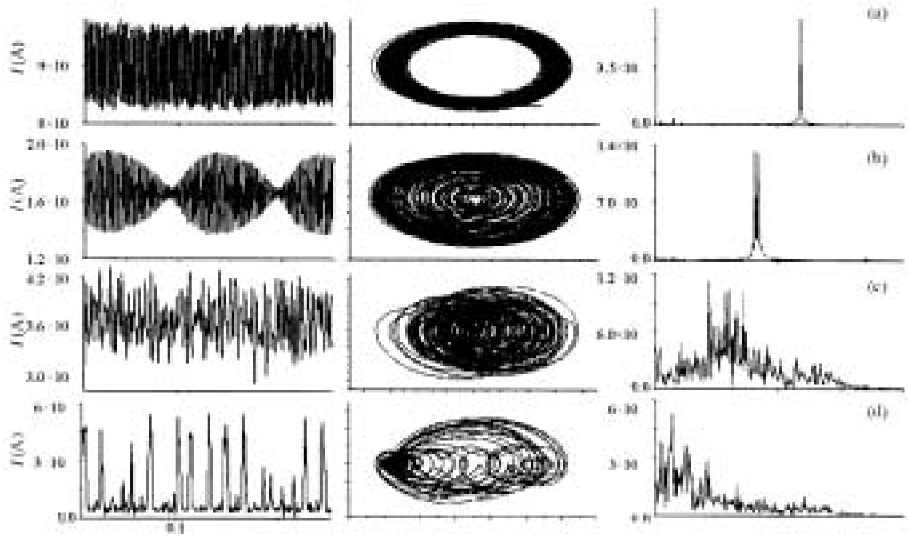

Figure 4. Temporal realizations, phase portraits and power spectra at different voltages applied to the sample: (**a**) 20.8 V; (**b**) 31.4 V; (**c**) 102.4 V; (**d**) 107.5 V.

A smooth transition from the ohmic to superlinear mode can be clearly seen, with current oscillations appearing when the I–V characteristic passes to sublinearity (figure 5a). As already mentioned, high-amplitude noises appear in a sample before S-switching, and the S-switching itself occurs in the form of high-amplitude oscillations similar to coherent oscillations (figure 5b). Two branches of the I–V characteristic (ascending and descending) form a limit cycle. Further increase in voltage leads to cycles with periods of 2 and 3 (figures 5c and d), and the noise component starts to grow steeply again, which disrupts the coherence of oscillations and leads to S-type behaviour (figure 5e). Positive branches of the S-shaped portion are filled with high-amplitude noise, which is confirmed by the power spectrum. Further increase in the voltage parameter gives rise to a second S-type portion (figure 5f), on whose positive branch the noise decays gradually to zero. It should be noted that the ascending and descending branches of the I–V characteristic demonstrate considerable hysteresis of about 25% in both S-switching portions.

3. Discussion and conclusion

The presented experimental data fully confirm the theoretical model [1,2]. Three operation modes have been found in Au-compensated p-Ge: ohmic, quenched, and transit-time. The existence of single-, double-, and multi-subdomain states and order–disorder–order transitions via intermittency or some unconventional scenario of transition to a chaotic state has been established. A second portion with S-switching is revealed in the current–voltage characteristic.

The physical mechanisms explaining the results presented above can be reduced to the following. The portions of I–V characteristics, extending as far as the first

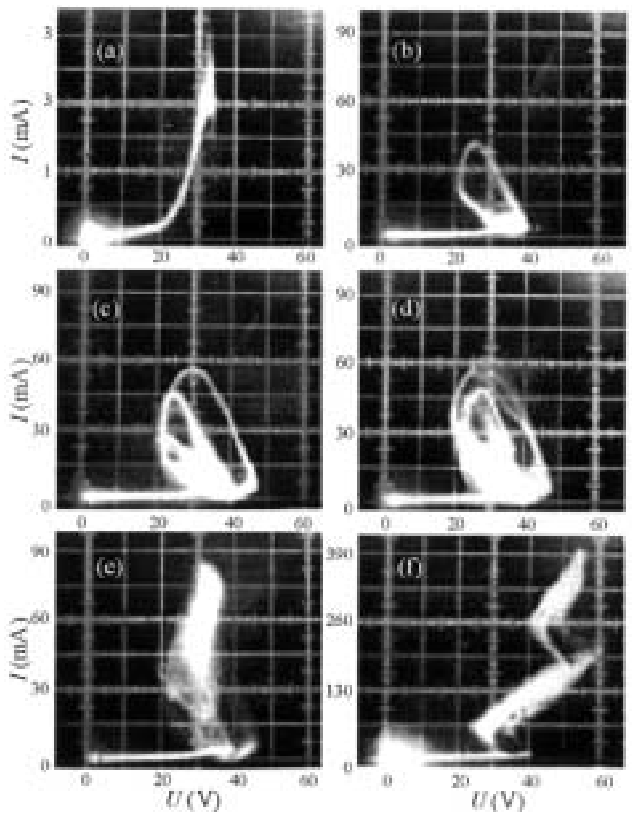

Figure 5. Evolution of the I–V characteristic with increasing applied voltage.

S-switching, and the recombination instability of the current in the two-parametric space, typical of this part of the characteristics, are in good agreement with the theoretical model [1,2]. We can explain the first S-switching in terms of Stafeev's mechanism [5]. Injection of non-equilibrium carriers and exposure of a sample to high-intensity light result in filling of the gold-related level in Ge at $E_1^{\mathrm{Au}} \approx 0.15$ eV and, therefore, cause sharp rise in the lifetime of minority carriers, i.e., electrons in the case in question. The appearance of a second S-type portion in the I–V characteristic, in whose formation the second deep level at $E_2^{\mathrm{Au}} \approx 0.2$ eV lying below the conduction band bottom may be involved, is not easy to understand physically, since no second region of S-type behaviour can be observed in samples with contact spacing greater than 3 mm and less than 1 mm. Possibly, in the sample of certain length the noise-induced non-equilibrium phase transition in the form of S-switching occurs caused by characteristic spatial-temporal scales. The multistability of I–V characteristics may be related to the appearance of tricritical points in the parametric space [16]. It has been shown [17] that injection can be used to raise the concentration of minority carriers, electrons in p-Ge(Au), compared with that in equilibrium, to such an extent that $\alpha = (n/p)(\tau n/\tau p) \gg 1$ (n and p

are the electron and hole concentrations, τn and τp are their lifetimes), which is the necessary condition for excitation of recombination waves [18]. It should be noted that the power spectra show a rise in the intensity of low-frequency noise before the S-switching, which is similar to the build-up of long-wavelength fluctuations in phase transitions (figure 4d).

Acknowledgements

The study was supported financially by the Russian Foundation for Basic Research, grant No. 02-02-17817. Authors would like to thank the Center for Collective Use of Institute of Physics for technical assistance.

References

[1] Ken-ichi Oshio and Hideo Yahata, *Phys. Soc. Jpn.* **65**, 1490 (1996)
[2] Ken-ichi Oshio and Hideo Yahata, *Phys. Soc. Jpn.* **67**, 2538 (1998)
[3] Jiang Zongfu and Ma Benkin, *Phys. Rev.* **B44**, 11072 (1991)
[4] E Mosckidle, R Feldberg, C Knudsen and M Hindsholm, *Phys. Rev.* **B41**, 2298 (1990)
[5] V I Stafeev, *Fiz. Tverd. Tela.* **5**, 3095 (1963)
[6] O V Konstantinov and V L Perel, *Fiz. Tverd. Tela.* **6**, 3364 (1964)
[7] O V Konstantinov and G V Tsarenkov, *Fiz. Tverd. Tela.* **8**, 1867 (1966)
[8] V L Bonch-Bruevich, *Fiz. Tverd. Tela.* **8**, 1753 (1966)
[9] I V Karpova and S G Kalashnikov, *Pis'ma Zh. Eksp. Teor. Fiz.* **6**, 954 (1967)
[10] I A Kurova and M Vrana, *Fiz. Tekh. Poluprovodn.* **1**, 1095 (1967)
[11] B K Ridley and R G Pratt, *J. Phys. Chem. Solids.* **26**, 21 (1965)
[12] I V Varlamov, V V Osipov, E A Poltoratskiy and A E Rzhanov, *Fiz. Tekh. Poluprovodn.* **4**, 2195 (1970)
[13] I V Karpova, V A Sablikov and S M Sirovegin, *Fiz. Tekh. Poluprovodn.* **22**, 609 (1988)
[14] S Bumeliene, J Pozela and A Tamasevicius, *Phys. Status Solidi* **B134**, K71 (1986)
[15] M J Feigenbaum, *J. Stat. Phys.* **19**, 25 (1978); *J. Stat. Phys.* **21**, 669 (1979)
[16] E School, *Nonequlibrium phase transition in semiconductors* (Springer, Berlin, 1987)
[17] I V Karlova and S M Sirovegin, *Fiz. Tekh. Poluprovodn.* **16**, 1601, (1982)
[18] O V Konstatinov, V K Perel and G V Tsarenkov, *Fiz. Tverd. Tela.* **9**, 1761 (1967)