ISSN 1063-7850, Technical Physics Letters, 2018, Vol. 44, No. 6, pp. 465–468. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © I.A. Prudaev, M.G. Verkholetov, A.D. Koroleva, O.P. Tolbanov, 2018, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2018, Vol. 44, No. 11, pp. 21–29.

Charge Carrier Transport and Deep Levels Recharge in Avalanche S-Diodes Based on GaAs

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Received February 15, 2018

Abstract—Carrier transport and deep-level recharging in semiconductor avalanche *S*-diode structures have been investigated. Gallium-arsenide n^+–π–ν–*n* structures with the diffusion distribution of deep iron acceptors have been studied. It has been found by solving the continuity and Poisson equations with the use of a commercial software that the electron injection affects the avalanche breakdown voltage and the space-charge region broadens due to capture of avalanche holes on negative iron ions in the π-region. It is demonstrated by comparing the results of numerical calculation with the experimental data that the *S*-shaped *I*–*V* characteristic of the diffusion avalanche *S*-diodes cannot be explained within the previously proposed mechanism of capture of avalanche holes on the deep iron levels.

DOI: 10.1134/S106378501806007X

An avalanche *S*-diode is a semiconductor switch with a *S*-shaped *I*–*V* characteristic under reverse bias. Commercial *S*-diodes allow commutating voltages of 50–700 V and currents of 0.1–50 A for times of 0.1–1.5 ns at maximum pulse repetition rates of 1–300 kHz [1]. The avalanche *S*-diode is based on the π–ν–*n* GaAs structure with deep acceptors in the π and ν regions (chromium, iron, copper, or manganese [1–3]). The effect of subnanosecond switching in the avalanche-breakdown mode was found first in [4] for Fe-doped GaAs. Some authors have attributed the *S*-diode switching to the recharging of deep centers in the avalanche-breakdown mode, which is accompanied by space charge region (SCR) narrowing [1, 2], and used a theory or recharging of the *p*–ν–*n* semiconductor structures via recharging of the deep acceptor in the ν-region during the avalanche breakdown [5]. This Letter is the first to present the results of numerical simulation of charge transport and deep acceptor recharging during the reverse current flowing in the GaAs-based n^+–π–ν–*n* *S*-diode structures [6]. The later-developed GaAs sharpening diodes [7] and bipolar GaAs avalanche transistors [8] are analogs of such devices.

In the investigations, we used a TCAD Synopsys software to solve a system of continuity and Poisson equations on a grid with a spacing of 10–200 nm. In the calculation, we took into account the effects of generation of carrier in accordance with the Shockley–Read–Hall model and avalanche-generation mechanism with the following field (*E*, V/cm) dependences of electron- and hole-ionization coefficients (cm^{-1}):

$$\alpha_n(E) = 4\times10^6 \exp\left(-\frac{2.3\times10^6}{E}\right)$$

$$\text{and}\quad \alpha_p(E) = 1.34\times10^6 \exp\left(-\frac{2.03\times10^6}{E}\right).$$

The impurity distribution corresponded to the typical diffusion structures used for low-voltage avalanche *S*-diodes [1, 3–9].The iron distribution profiles were specified by the erfc function on the basis of the data reported in [10]. The deep iron acceptor ionization energy was chosen to be 0.5 eV from the top of the valence band. The diode area was 10^{-6} cm^2. The simulation was carried out for four structures (see the iron and shallow acceptor distribution profiles in Fig. 1a). In Fig. 1a, the ν-type region have conventional boundaries (one of the boundaries is specified by the crossing point between the shallow donor and deep iron acceptor profiles).

The *I*–*V* characteristics of the structures are shown in Fig. 1b. The calculation showed that the change in electron (σ_n) and hole (σ_p) capture cross sections within $\sigma_n = (3–100) \times 10^{-19}$ cm^2 and $\sigma_p = (1.5–100) \times 10^{-16}$ cm^2 does not lead to a noticeable quantitative variation in the *I*–*V* characteristic. These limits are fairly broad and include the available experimental values. The inset in Fig. 1 shows the dependence of

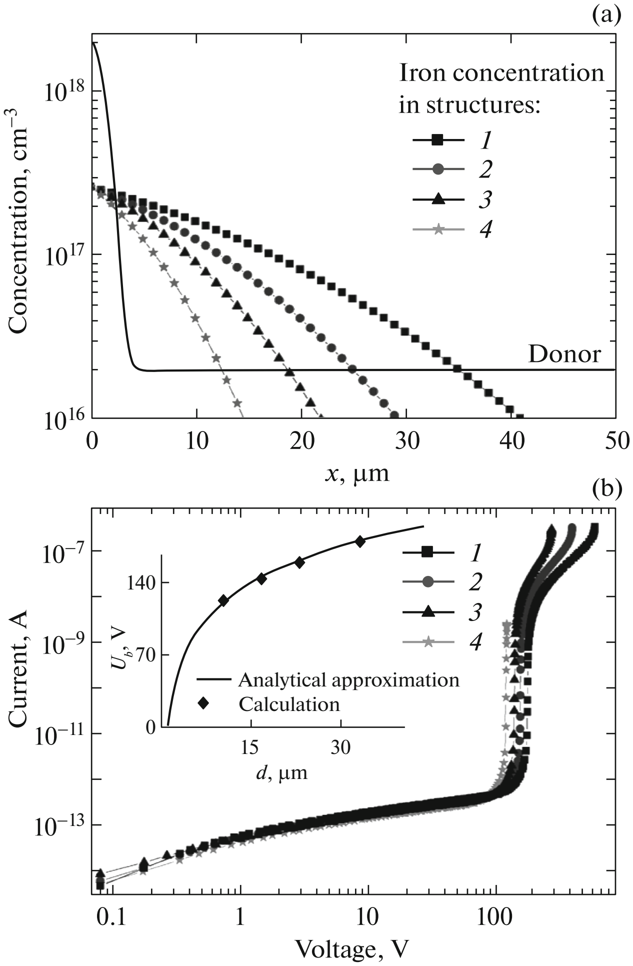

Fig. 1. (a) Shallow donor and deep iron acceptor distribution profiles in four investigated structures and (b) their reverse I–V characteristics. Curve numbers correspond to the structure numbers. Inset: dependence of the avalanche breakdown voltage on the high-resistance layer thickness.

avalanche breakdown voltage U_b on high-resistance layer thickness d, which is well-approximated by logarithmic function $U_b(d) = U_0\ln(d^2/r)$ at the parameters $U_b = 25.6$ V and $r = 1\ \mu\text{m}^2$ (the avalanche-breakdown current was taken to be 5×10^{-12} A).

Comparison of the I–V characteristics with the experimental data reported in [1–3, 9] shows that, at low voltages, they are in qualitative agreement. Up to 0.2–0.3 V, there is an almost linear part, and, at voltages of $1 < U < 80$ V, a generation part is observed (the voltage dependence of the current is $I \sim U_m$, where m is $\approx 1/2$). At higher voltages (above 80 V), the current sharply grows due to impact ionization. In the experiment, the current growth caused by the avalanche breakdown is observed already at 20–50 V (soft breakdown), which is related to the microplasma character resulting from the nonuniform impurity distribution. In the calculation, the nonuniformity of the impurity distribution was ignored. Nevertheless, we obtained good agreement with the experiment for the dependence of the avalanche breakdown voltage on the high-resistance layer thickness: the dependence is a weakly logarithmic function, and so the thickness variation by a factor of 3.5 leads to a minor (about 30%) change in the breakdown voltage [1, 9].

Analysis of the free carrier distribution showed that the breakdown voltage decreases due to carrier injection from the n^+–π junction. Figure 2a shows voltage dependences of the electron density for one of the structures (in the other structures, a qualitative coincidence is observed). It can be seen that voltage growth leads to an increase in the small electron density in the π region until the bias attains values close to U_b. After reaching U_b, the π–ν junction resistance decreases and the electron density sharply increases over the entire π region (by three to six orders of magnitude). Since the avalanche generation rate is proportional to the free electron density, the electron-injection effect should lead to a decrease in the field required for the avalanche breakdown. This results in the breakdown voltage decreasing with decreasing π-region thickness that is observed both in the experiment [9] and in the calculation.

The hole density distribution presented in Fig. 2b shows that the avalanche breakdown leads to a sharp growth of the hole number in the SCR. Here, the dashed line shows the SCR boundary shift from the side of the π region upon voltage variation. The inset in Fig. 2b presents the calculated data for the average hole density in the π and ν regions of the SCR. A sharp hole density jump leading to the recharging of deep iron levels is observed in the range from 150 to 200 V ($150 < U_b < 200$ V for structure no. 1).

The main qualitative difference between the calculated and experimental I–V characteristics is observed at $U > U_b$. It follows from Fig. 1b that, in this range, there is a step accompanied by an increase in the voltage on the structure. In the experiment, in most cases, the structure switches to the conducting state at $U =$ 100–200 V ~ U_b, which is accompanied by a decrease in the voltage (the S-shaped I–V characteristics). The step is caused by the SCR broadening toward the π-region due to the capture of avalanche holes to the negatively charged iron levels.

The field and space charge density distributions in one of the structures are shown in Fig. 3. In the other structures, the distributions are qualitatively similar. It can be seen in Fig. 3a that, as the voltage increases above U_b, the field distribution symmetry is violated and its maximum shifts to the π region. Thus, under stationary conditions, a broad ν-type region forms. The charge density distribution shape (Fig. 3b) confirms the electronic type of the conductivity of the broadening SCR: a section with almost uniform ion distribution appears between two extrema and the total charge of ions is positive.

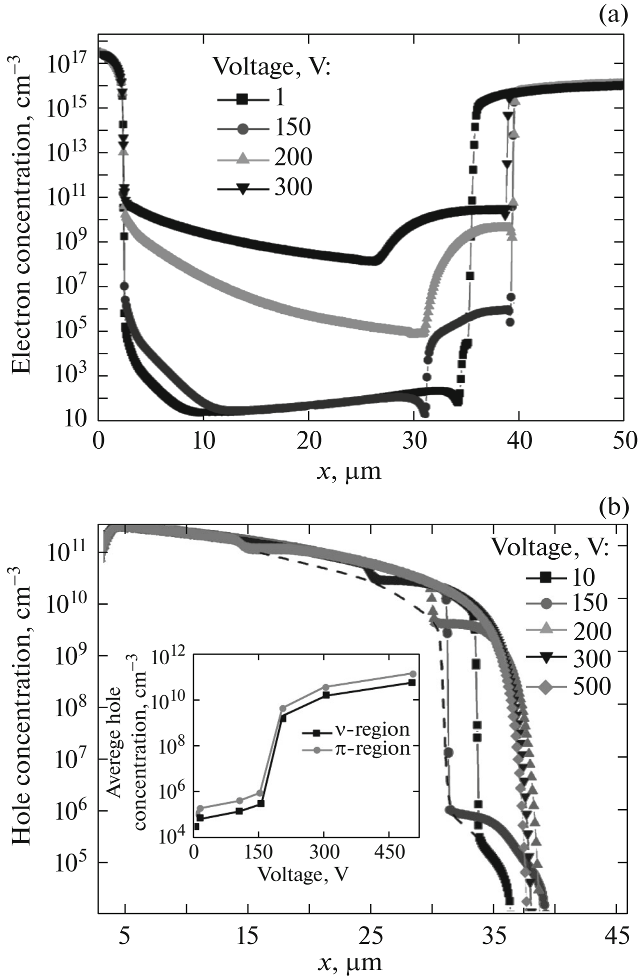

Fig. 2. (a) Electron and (b) hole density distributions in structure no. 1 at different applied voltages. Inset: bias dependence of the average hole density in the π and ν SCR regions.

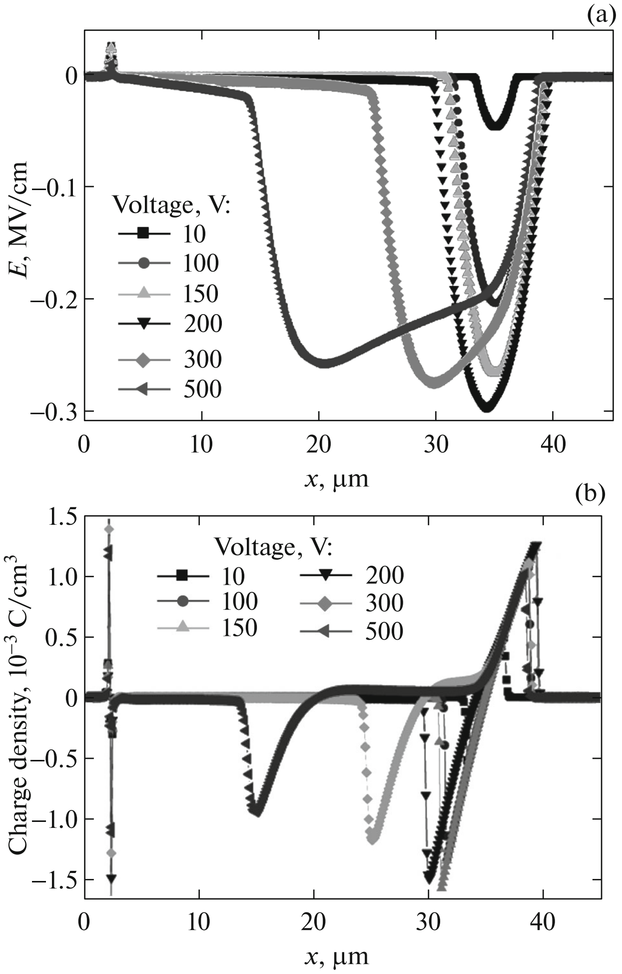

Fig. 3. (a) Field strength and (b) charge density distributions in structure no. 1 at different applied voltages.

We would like to emphasize the following. Previously, the hole capture in structures of the avalanche *S*-diodes was assumed to occur in the ν region. According to the proposed mechanisms [1, 2, 5], this leads to narrowing of the SCR and formation of the *S*-section. However, our calculations showed that hole capture occurs, first of all, in the π-region, which leads to an opposite effect, i.e., SCR broadening. In addition, it was established that this effect is insensitive to the capture cross section (within reasonable limits). In our view, this mainly originates from two factors, which were ignored in [1, 2, 6]. First, the SCR field leads to the emission of avalanche holes to the π-region. In this case, there are significantly more holes than in the ν-region. Second, in real diffusion structures, the negatively charged acceptor density in the ν region can be much lower than in the π-region due to the sharp coordinate dependence of the erfc-function of the deep impurity distribution. Under these conditions, it is obvious that the probability of avalanche-hole capture to negatively charged deep acceptors, which depends on the product of hole and negatively charged ion densities in the π-region, will be significantly higher.

In addition, the results obtained indicate that the experimentally observed switching of avalanche *S*-diodes is not caused by deep center recharging (in which case there would be some unconsidered factors). In the literature, other mechanisms of GaAs-structure switching to the open state in the avalanche breakdown mode have been reported, including the propagation of impact ionization waves or generation of collapsing Gunn domains in the avalanche regime [7, 8, 11, 12]. The former mechanism is improbable, since avalanche *S*-diodes switch under a developed avalanche breakdown and without significant overvoltages. The latter mechanism is more feasible and requires further verification.

Acknowledgments. This study was supported by the Ministry of Education and Science of the Russian Federation, state assignment no. 11.2247.2017.

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Translated by E. Bondareva