CONCERNING THE DETERMINATION OF THE MECHANISM OF ELECTRIC BREAKDOWN IN SEMICONDUCTORS

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Electric breakdown in semiconductors was investigated, in the main, with the aid of experiments with p-n junctions. It has been established that in narrow p-n junctions the breakdown is connected with the tunnel effect (Zener current), and in broad ones with impact ionization [1 - 4]. In the transition region between the two mechanisms, the free carriers produced as a result of the tunnel effect also induce a cascade, just as thermal carriers. Up to the present time, the breakdown mechanism in the transition region was deduced from a large number of indirect characteristics, which made it possible to estimate the character of the phenomenon only qualitatively [1 - 5]. In the present paper we propose, for the first time, a method of measuring the Zener current in the presence of a developed cascade breakdown; this method makes it possible to determine uniquely the electric-breakdown mechanism.

The high-frequency fluctuations of the current $i^0 = i_s M$ flowing through the p-n junction during the breakdown are determined by the shot fluctuations of the saturation current i_s and by the fluctuations of the multiplication coefficient M [6]. The thermal fluctuations in the ohmic resistances of the diode, and also the generation-recombination noise at frequencies above 10^4 Hz can apparently be neglected. According to [6], if $\omega\tau \ll 1$, the formula for the spectral density of the diode current fluctuations, $S^0(I^0)$, can be written in the form

$$S^0(i^0) = \frac{2ei^0}{\left(\frac{\omega T}{2}\right)^2 + \left(\frac{1}{M} + \frac{\Omega^2 \tau T}{4}\right)^2}, \qquad (1)$$

where T and τ is the time of passage of the carriers through the multiplication layer and through the transit space of the p-n junction, respectively, and $\Omega \sim \sqrt{i^0}$ is the characteristic frequency determining the oscillatory properties of the cascade-development process [7]. The first term of the denominator of (1) takes into account the finite cascade-development time, and the second takes into account the depression of the fluctuations by the space charge of the mobile carriers.

We verified the correctness of formula (1) experimentally using germanium diffusion diodes with symmetrical p-n junctions and with breakdown voltage V_{br} = 6 - 45 V in the frequency range (0.06 - 2) x 10^9 Hz. In calculating $S^0(i^0)$ with formula (1) we used the values of T, τ, and Ω calculated from the formulas of [7]. Recognizing that the saturation current in the investigated diodes is small ($i_s < 2 \times 10^{-8}$ A), the term 1/M in formula (1) can be neglected in the investigated frequency range ($\omega/2\pi > 10^7 > 1/\pi MT$). An investigation of about 50 diodes has shown that when V_{br} > 12 - 15 V the calculated and experimental values of $S^0(i^0)$ coincide within the limits of the measurement accuracy and the accuracy with which the noise can be referred to the p-n junction (on the order of ±25%) (see Fig. 1, curve 1). For diodes with V_{br} < 12 - 15 V the experimental $S^0(i^0)$ curves lower than the calculated ones. At currents $i^0 < i_1^0$ (i_1^0 - current corresponding to the extremum of the function $S^0(i^0)$), the xexperimental points do not decrease linearly with decreasing i^0, as would follow from (1), but in proportion to $(i^0)^3$ (see Fig. 1, curves 2 and 3). All this indicates that formula (1)

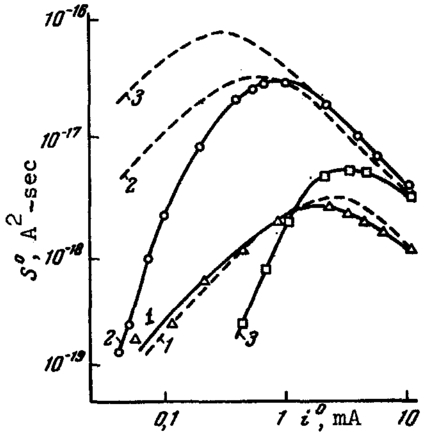

Fig. 1. Spectral density of current fluctuations vs. breakdown voltage and diode current. C = 0.13 pF, f = 200 MHz. Solid-experiment, dashed - calculation for $i_z = 0$. V_{br} = 41 (1), 12 (2) and 6.5 V (3).

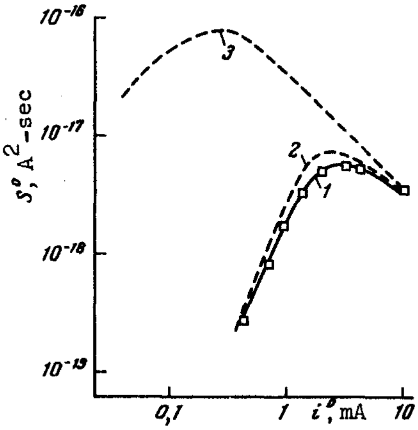

Fig. 2. Spectral density of current fluctuations vs. diode current. C = 0.13 pF. f = 200 MHz. V_{br} = 6.5 V. 1 - experiment; 2 - calculation for $i_z \neq 0$; 3 - calculation for $i_z = 0$.

is not applicable to p-n junctions with $V_{br} < 12 - 15$ V.

The inhomogeneity of the impurity concentration, which to an uneven distribution of the current over the p-n junction area, cannot explain the disparity between the experimental and calculated $S^0(i^0)$ curves for $V_{br} < 12 - 15$ V, since it is most strongly pronounced in the regions with the larger current density, where the noise suppression by the carrier space charge is appreciable, and does not influence the noise at low currents ($i^0 < i_1^0$).

An estimate shows that in germanium diffusion diodes with V_{br}=10 - 15 V the density of the Zener current becomes comparable with the density of the saturation current or else exceeds it. Since the Zener curent i_z initiate the cascade alongside the saturation current, it must be taken into account in the calculation of the multiplication coefficient M. If we take the multiplication coeffcient M in formula (1) to mean the quantity

$$M = \frac{i^0}{i_s + i_z}, \qquad (2)$$

then the aforementioned disparity between the experimental and calculated data can be satisfactorily explained. Indeed, when the breakdown voltage decreases the Zener current increases and at a specified diode current i^0 the multiplication coefficient decreases, as a result of which $S^0(i^0)$ decreases in proportion to $i^0M^2 \sim (i^0)^3$ when $i^0 < i_1^0$ and M is small ($M \ll 2/\omega T$). When $i^0 > i_1^0$ and the suppression of the fluctuations by the space charge of the mobile carriers is significant, the Zener current has little effect on $S^0(i^0)$.

Taking into account the good agreement between formula (1) and experiment when $V_{br} >$ 12 - 15 V, we can use formulas (1) and (2) to determine the Zener current. To this end it is necessary to substitute in (1) the experimentally obtained value of S^0, taken at $i^0 \ll i^0$, and then find the value of i_z. Since the intensity of the electric field changes little when the current i^0 changes, it can be assumed that i_z is practically independent of i^0. Using the obtained value of i_z, we can construct the entire $S^0(i^0)$ plot (see Fig. 2). A comparison of the experimental and calculated curves of Fig. 2 with and without allowance for the Zener current confirms the considerations advanced above. According to the preliminary data obtained by means of this method, the Zener current density in germanium diffusion p-n junctions with breakdown voltage 12 V ($E_{max} \approx 2.5 \times 10^5$ V/cm, where E_{max} is the electric field intensity at the center of the p-n junction) is of the order of $(0.5 - 1) \times 10^{-2}$ A/cm^2, and if $V_{br} = 6.5$ V ($E_{max} \approx 3 \times 10^5$ V/cm) its order is 1 - 2 A/cm^2.

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[1] A. G. Chynoweth and McKay, Phys. Rev. 106, 418 (1957).
[2] J. L. Miller, Phys. Rev. 99, 1234 (1955).
[3] A. P. Shotov, Zh. Tekh. Fiz. 26, 1634 (1956) [Sov. Phys.-Tech. Phys. 1, 1591 (1957)].
[4] A. G. Chynoweth, W. L. Feldmann, C. A. Lee, R. L. Logan, G. L. Pearson, and P. Aigrain, Phys. Rev. 118, 425 (1960).
[5] T. M. Singh, Solid State Electronics 11, 99 (1968).
[6] A. S. Tager, Fiz. Tverd. Tela 6, 2418 (1964) [Sov. Phys.-Solid State 6, 1919 (1965)].
[7] A. S. Tager, Usp. Fiz. Nauk 90, 631 (1966) [Sov. Phys.-Usp. 9, 892 (1967)].

DONOR ACTION OF DISLOCATIONS IN InSb

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The distinguishing features of plastic deformation in the crystal lattice of InSb make it possible to obtain in the crystal either an excess of α dislocations (terminating on a row of In atoms) or β dislocations (terminating on Sb atoms), depending on the polarity of the sample, the direction of the flexure axis, and the bending moment [1].

In our earlier investigation of the influence of plastic deformation by bending on the electric properties of InSb crystals (deformation temperature -200°C) [1] we observed an acceptor action of the α dislocations. It was assumed that the possible mechanisms of the observed phenomena could be one of the following:

1. Direct acceptor action of the dislocations (electron capture by the "bump couplings").

2. An increase in the number of active acceptors as a result of diffusion and redistribution of the impurities in the dislocation field, and the increase of the number of point defects.

To check on the foregoing mechanisms of acceptor action, n-type InSb crystals were subjected to plastic bending at a still lower temperature, -150°C, at which the diffusion rate is decreased. This revealed no acceptor action of either the α or β dislocations (Fig. 1). Subsequent annealing of these crystals at 350°C for three hours exerted an appreciable acceptor action and the crystal exhibited a p-type conductivity ($p = 8 \times 10^{14}$ cm^{-1} at 100°K). On the basis of these data, it can be assumed that the change of the type of conductivity of the sample is due not to direct acceptor action of the α dislocations, but is due to the