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# MODELING MICROPLASMAS P-N JUNCTION

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## INTRODUCTION

Indeed, already in the very first studies of the avalanche breakdown of p-n junctions and Schottky diodes, it was shown that the breakdown in them is highly localized. The local breakdown region has small geometric dimensions and significantly lower breakdown voltage compared to homogeneous regions).

Despite the fact that the processes of microplasma breakdown were studied in a number of works [1;2;3], the clarity both in the mechanisms of the occurrence of an MF and their influence on the degradation processes has not been fully studied. If a voltage V is applied to the n-region of a p-n junction, in relation to the potential of the p-region, then such a p-n junction is called back-biased [4]. If the breakdown voltage of the microplasma Vm through the p-n junction will flow in the form of pulses with an average frequency of 104 -105 Hz [5;6].

This nature of the current flow through the microplasma in the initial section of the breakdown leads to the appearance of discontinuities and kinks in the current-voltage characteristic (CVC) of the p-n junction. The appearance of microplasmas is accompanied by the emission of light and hot electrons. Vm breakdown of the p-n junction is determined mainly by microplasmas. Each next break in the CVC curve is associated with the appearance of a new microplasma, and with each of its inclusions, the CVC steepness increases, since this leads to a decrease in dynamic resistance.

The authors of [7] showed that the breakdown voltage of microplasmas Vm increases with increasing temperature, and the thermal voltage coefficient (TCV) of the breakdown of the microplasma is greater, the higher the breakdown voltage of the diode. This indicates that the breakdown of the microplasma has an avalanche character. Since microplasmas appear at voltages lower than the breakdown voltage of the entire p-n junction Vm, a large current will flow through the MP channel. This process causes local heating of the crystal at the site of the microplasma, which will accelerate the diffusion of ions. All this can cause the p-n junction or the Schottky diode to fail. Therefore, it is necessary to take efforts to eliminate low-voltage microplasmas in semiconductor devices.

Since microplasmas significantly reduce the quality of semiconductor devices, it is important to find out the reason for their occurrence. It is clear that microplasmas are apparently caused mainly by imperfections in the crystal lattice - dislocations, inclusions of dielectrics and metals in the region of the p-n junction, Objects and methods for studying microplasma instability [8].

During the measurements, industrial batches of avalanche-transit diodes (ATDs) with the p+-n-n+ structure were used. The thickness of the n-region exceeded the length of the space-charge region (SCR) of the semiconductor, so that the analyzed diodes turned out to be “unpunctured” during working mixtures, that is, in all modes, the electric field near the n+-region is equal to zero.

Diodes in which the electron concentration in the lightly doped base was ~2*1016cm-3 and the avalanche breakdown voltage was 45V were analyzed in the most detail.

At the same time, the consideration of the MF in junctions with a breakdown voltage of 26V and 20V indicates a similar physical picture as in the case of Vm=45V.

The main parameters of the APD and the structures on the basis of which they were fabricated are given in Table 1. Information about the technology of their manufacture is also given here.

The objects of study were also silicon zener diodes obtained on the basis of a p-n junction using alloy technology, the avalanche breakdown voltage in them varied in the range from 8V to 30V.

Since all the characteristic features of the current-voltage characteristics of the studied transitions, as it turned out, are similar (except, of course, for the value of Vm), in the further presentation of the material, we will only talk about zener diodes of the D815E, D815D type [9], for which Vm = 12 V and Vm =15 V respectively.

In this case, the electron concentration in the lightly doped n-base was about 7·1016 cm-3. The area of the p+-n-junction in this case was about 4 mm$^{2.}$

To compare the characteristics of the magnetic field, in a number of cases, we studied arsenide - gallium LPDs with a p-n junction [10].

The measurements were carried out on a microplasma characterograph in the mode of a current generator. This technique makes it possible to clearly register individual MPs by the form of the CVC on the oscilloscope screen (their number usually varied from 2 to 15). If necessary, the CVC could be displayed for recording on a recorder.

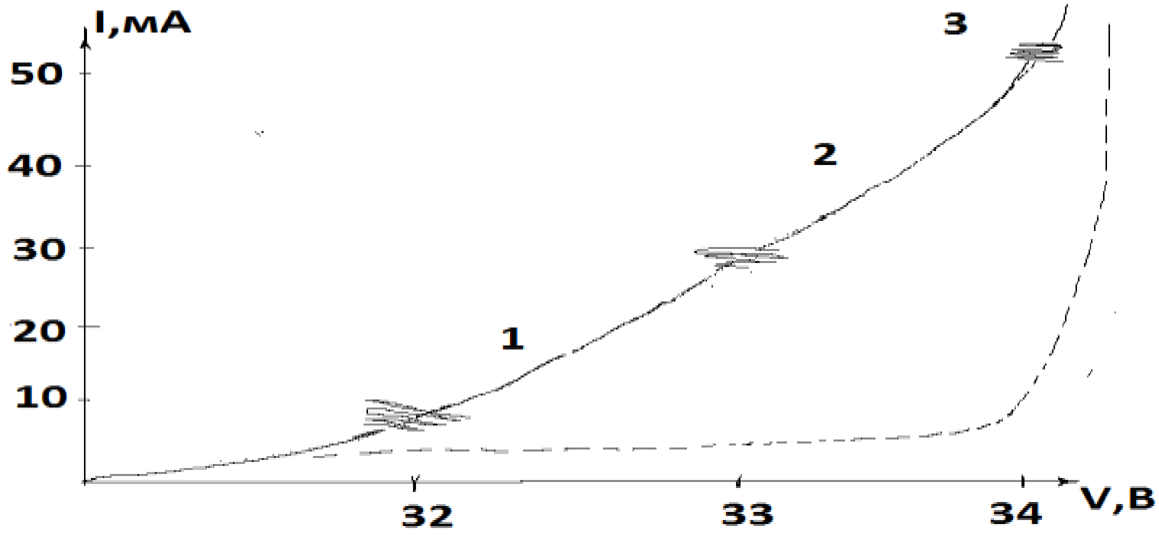

**Fig .1. Typical CVC of a diode observed on the screen of a microplasma curve tracer 1,2,3-first, second, third MP. The dotted line indicates the ideal CVC (no MP)**

The slope of the I–V characteristics in the pre-breakdown region determines such an important MF parameter as their differential resistance R, and by definition, we can write:

$$R = \frac{dU}{dI} \quad (5)$$

At the same time, the value of R can be determined experimentally by the method of modulation differentiation.

In the event of an MF, their overvoltage (the difference between the voltages of the developed breakdown VM and the voltage of the beginning of the MF (was in the range from 0.5V to 2V.

The measured values of the differential resistance of the MF of the considered junctions varied within 0.2–15 kΩ for different samples from different technological batches. The accuracy of determining the value of the differential resistance was no worse than 10%. Our task was to determine the geometric MF and the inhomogeneity of the current and temperature in their channels.

To estimate the geometric local breakdown regions, the MF is usually represented as a cylindrical region of length Lm, coinciding in the “non-punctured” case with the width of the space charge region at the breakdown voltage and diameter dm.

It is believed that the electric field strength varies along the cylinder, but does not change in the radial direction [2]. The values Lm and dm are effective and, in particular, it is known from [11, 12] that dm increases with the applied voltage.

The effects of microplasma breakdown can arise due to the deviation of the geometry of p-n junctions from flat [13]. In [14], an edge inhomogeneity with dimensions exceeding the thickness of the space charge region, the electric field of which is greater than in the middle part of the diode, was considered.

The possibility of the emergence of microplasma in Schottky diodes and sharp p-n junctions in the presence of roughness of the interfaces, leading to the appearance of strong electric fields comparable in magnitude to breakdown ones, is theoretically predicted. For a real three-dimensional inhomogeneity with dimensions ly=lx=l in the radial direction and h in height, the electric field obtained in [14] is determined by the formula:

$$E(x,y)=E_s\left(1-\frac{X}{L}\right)+E_0\,\frac{\pi\cdot h\cdot\sqrt{2}}{l}\,l\,\frac{-\pi\cdot x\cdot\sqrt{2}}{l}\cos\frac{\pi\cdot y}{l}\cos\frac{\pi\cdot x}{l} \quad (1)$$

And if we compare the correction for inhomogeneity at $\frac{h}{l}\sim 0{,}5$ with the maximum

value of E at z=0 and x=h, then it will be said that the correction for inhomogeneity is 20%. Taking into account the strongly non-linear dependence of the impact ionization coefficient on the magnitude of the electric field, such an inhomogeneous correction becomes significant.

The temperature of the MP channel compared to the ambient temperature is determined by the expression:

$$\Delta T_0=\Delta T_1+\Delta T_2=\frac{R_{T1}\cdot\Delta J}{\beta\cdot V_M}+\frac{R_{T2}\cdot\Delta J}{\beta\cdot V_M} \quad (2)$$

Where Vm is the microplasma breakdown voltage; RT2, ∆T2 - thermal component of the diode resistance and its heating as a whole as a whole; RT1, and ∆T1 are the corresponding values for the microplasma channel. The value of ∆T0 makes it possible to determine from (8) the temperature of the microplasma channel, RT2 is easily determined from the thermal resistance known from the experiment $R_{t2}=\beta\cdot U_{м}^{2}\cdot l\cdot R_{T2}$ . (3)

The value of the total series resistance is found experimentally which, $R_T=R_{T1}+R_{T2}$ in addition to, includes the spreading resistance R0 and the SCR resistance Rc, and the determination of RT is difficult experimentally.

The most reliable way to find the value of ∆T0 for ATL is to compare the experimental and theoretical expressions for Rs and its components, taking into account the actual geometric structure of the MP. In [15], RT were calculated without the assumption of uniform heat release in the MP channel.

It is shown that the change in temperature in the microplasma is determined only by the geometric characteristics of the magnetic field - its radius, length and value of the X0 coordinate of the point where the temperature is measured. It is also shown that a large error for thin MFs, for which dm <h.

The MF temperature in the region of the maximum field is determined by the thickness of the space charge region, which is proposed to be called the MF length. If the thickness of the weakly doped region d is such that its puncture occurs, then d should be taken as the length of the magnetic field.

In the case of Lm > dm, the main role in establishing the temperature in the MT channel is played by heat transfer in the semiconductor, and the value of ∆T1 is determined only by the value of the thermal conductivity coefficient of the semiconductor. Taking into account the three-dimensionality of the distribution of the electric field for calculating Rc by the formula $R_c=\int_{L_м}^{L}\frac{\Delta E(x)dx}{\Delta J}$ , (4) где $\Delta E_{(x)}$ was chosen as the electric field of a charged cylinder with a diameter dm and at dm <<L, Rc becomes negligible.

In addition, such an expression for R0 is obtained in the case of a three-dimensional MT model. Then, by comparing the theoretical and experimental data, the geometric dimensions of the MF in the LTD based on gallium arsenide were determined. At the same time, measurements have not yet been carried out for the zener diode and silicon-based LTD.

For further analysis, we will have the necessary standard expressions that allow us to find the breakdown voltage, the avalanche multiplication factor.

The inverse I–V characteristics of silicon zener diodes were measured in the voltage generator mode, then, in order to isolate sections with an MF, the I–V characteristics were differentiated, and the first and second derivatives, together with the initial characteristic, were presented in one figure, Fig. 2

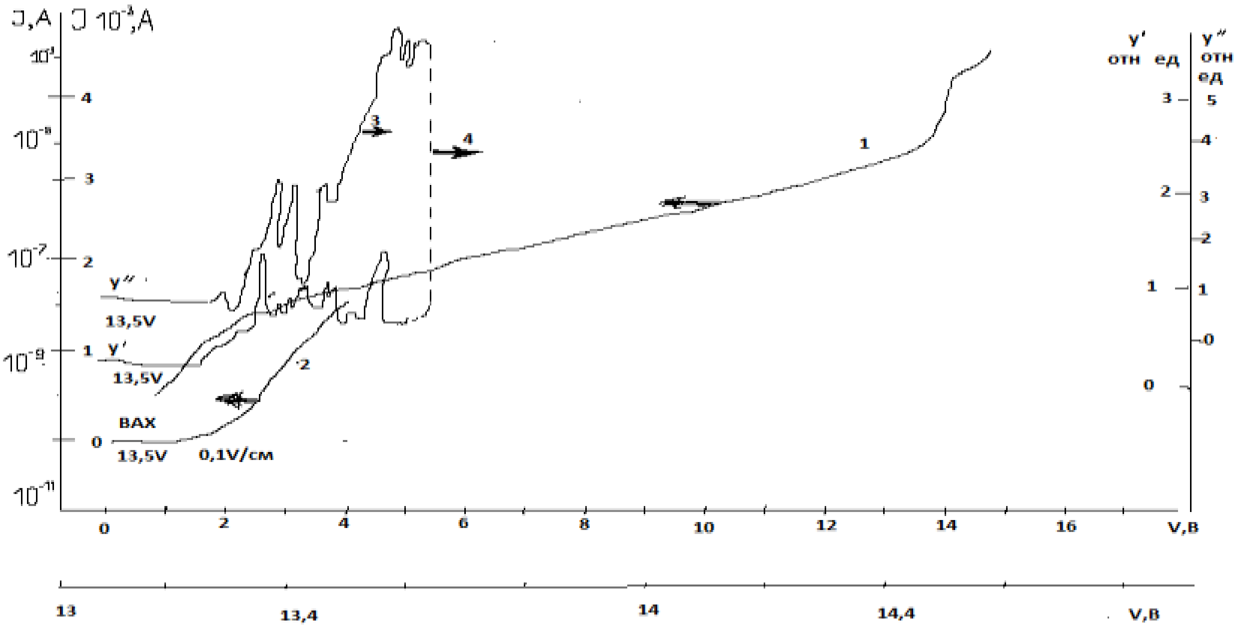

**Fig 2. Typical dependences obtained using a microplasma curve tracer***:*

1VAC of a silicon Zener diode on a semi-logarithmic scale.
2. Plot CVC near the value of the breakdown voltage (linear scale).
3. Graph of the first derivative of the CVC near the breakdown voltage value (linear scale).
4. Graph of the second derivative of the CVC near the breakdown voltage value (linear scale).

The directions of the arrows indicate which y-axis (right or left) should be used when interpreting the graphs. The lower stress scale refers to curves (2), (3), (4).

This made it possible to directly find also important characteristics of the MF, such as their breakdown voltage Vm and differential resistance Rs.

Usually, on average, from 3 to 10 MP was recorded, which really confirms the significant inhomogeneity of the p-n junction. The breakdown voltage Vm of the first MF in the diodes under study was less than the breakdown voltage of the entire diode Vb by about 0.7-3V. The differential resistances of the MP Rs varied from 0.2 to 10 kOhm, and their value randomly depended on the order of the MP in one or the p-n junction, although, on average, the first MPs had larger Rm values compared to the subsequent ones.

Let us further evaluate the effects associated with the inhomogeneity of the current flow and temperature in the channels of the MF of the Zener diodes under study. For this purpose, it is necessary to determine the geometrical parameters of the MF (its length and diameter), as well as the overheating ∆Tm of the MF channel. Since the p*-n junction is not shed, in this case the length of the MF coincides with the thickness of the non-equilibrium depletion layer in the n-region and at a breakdown voltage of 14V. B (carrier concentration of the order of 7.1016 cm-3) is equal to 0.5 µm.

The value of dm will be determined by the method proposed by us in [16]. For this theoretical dependence of the value of the differential resistance of the MF Rs and its series components of the thermal resistance Rt and the SCR resistance Rc on the diameter dm for this type of p-n junction is shown in Fig. 3. As the estimates show, in this case, the spreading resistance component R0 and can be neglected, and therefore the dependence R0(dm) is not shown in Fig. 3.

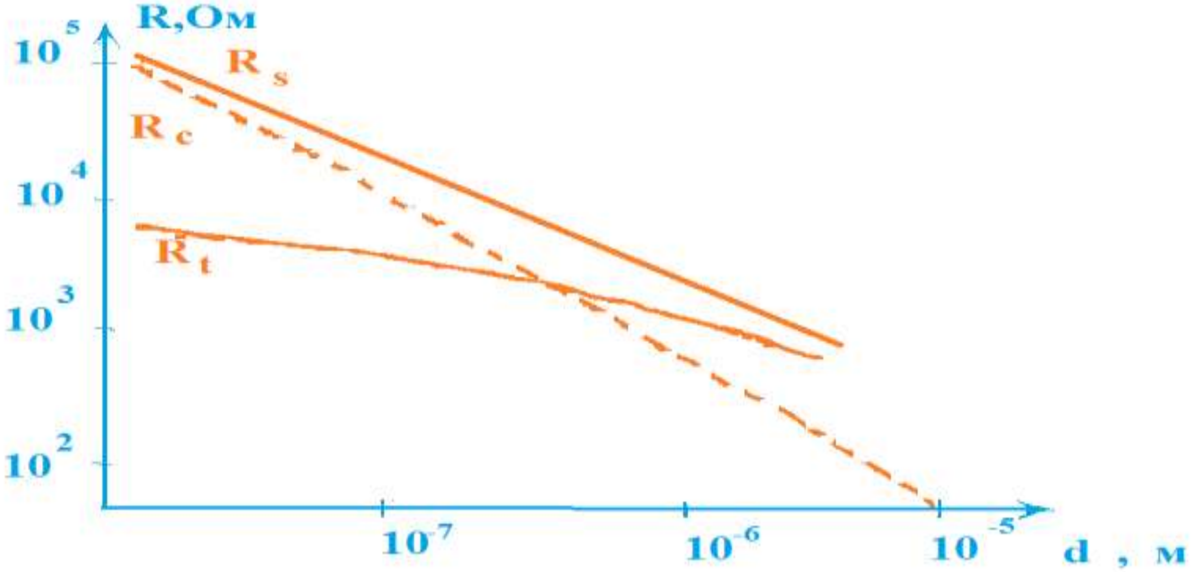

**Fig-3. Dependence of the differential resistance of the MP of its series components Rt and Rc on the diameter of the MP for silicon Zener diodes (n=7*1016cm-3, VB=15V)**

Note that the method of determining the MF diameters dm by comparing the experimental values of Rs with the theoretical dependences Rs(dm) has a number of advantages over the methods proposed (see, for example, [17]). First of all, the proposed method for controlling the geometric dimensions is non-destructive; it does not require special processing of samples before studying the characteristics of the magnetic field, as is necessary when determining by optical methods. In addition, for low-voltage diodes, which are the Zener diodes under study, pulse measurements in order to find dm [17] are also impossible due to capacitive limitations. Analyzing the current-voltage characteristics obtained by us, we find that the differential resistances of the MP Rs vary in a wide range of values: from 0.2 to 10 kOhm. First of all, this indicates a wide range of inhomogeneities of the p+-n junction interfaces responsible for the occurrence of the magnetic field. Taking into account the experimental values of Rs, using Fig. 4, we find that as Rs increases from 0.2 to 10 kΩ, the diameters of the magnetic field decrease from 10 to 0.6 μm, that is, in diodes manufactured using alloy technology, a wide range of inhomogeneity sizes is manifested.

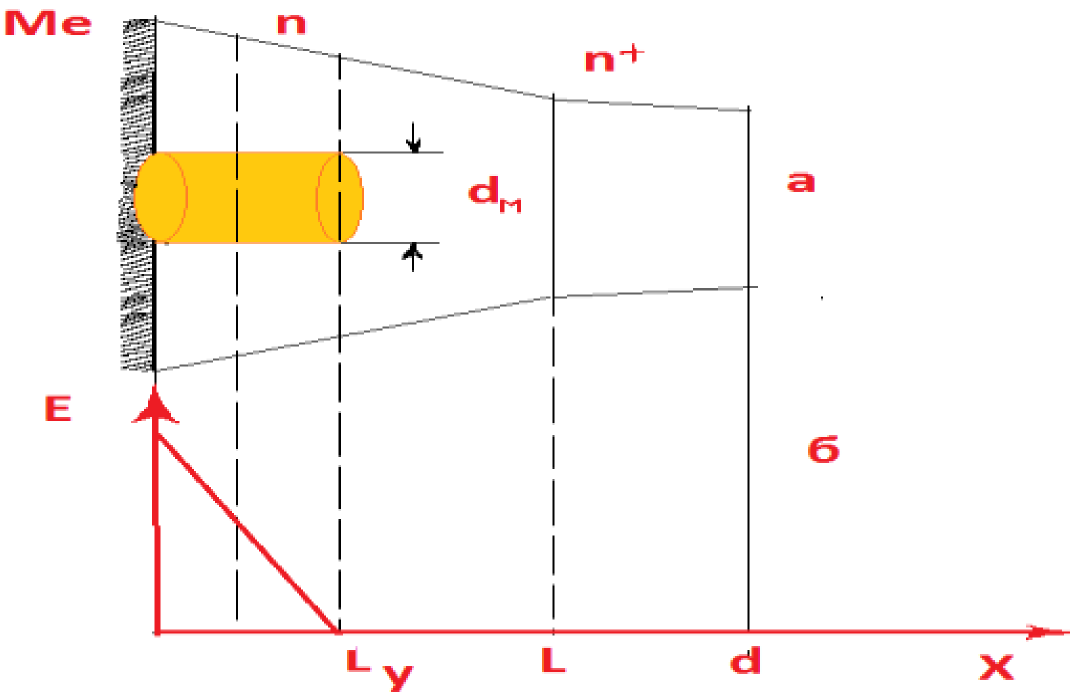

**Fig. 4. Schematic cross-section of the Schottky diol obtained using the reverse mesa structures technology (a); electric field directivity distribution E(x) in the direction normal to the transition plane (b);**

The following notation has been introduced:

M - metal, n - base area of the device with thickness d, Microplasma is represented by thickness d.

The microplasma is represented as a cylinder with a diameter dm and a length LM coinciding with the thickness of the SCR layer L, LU is the thickness of the multiplication layer.

Let us describe the characteristics of the MP under operating conditions close to the limit, but admissible. In this case (in contrast to [10]), an approach should be developed to describe the MF parameters in the mode of developed avalanche breakdown. This mode is characterized by relatively high current values (at such currents, the mobile charge density, in this case, electrons, is comparable to the charge density of ionized donors in the SCR (and the transition heating caused by it.

In this case, we used the following geometric model: the MP was presented in the form of a cylinder (diameter dm and length (see Fig. 4), from the side surface of which heat exchange with the rest of the semiconductor is possible. Further, when analyzing the characteristics of the MP, it should be taken into account that the breakdown voltage VV of such such an “elementary” diode in the operating mode is greater than the same value of VM but at room temperature.

The result obtained allows us to draw the following conclusion: the simulation of microplasmas in Si-based p-n junctions is directly related to the existence of large inhomogeneities comparable to the SCR thickness, which determine the size of the MF localization region. For diodes with a microrelief height h < 20 nm, a uniform breakdown occurred, while for diodes with h > 20 nm, a microplasma breakdown occurred. Thus, a uniform avalanche breakdown is observed in diode structures with a height of inhomogeneities (microrelief) h < 20 nm. At large values of h, areas of microplasma breakdown are formed in the pre-breakdown region. And this, in turn, reduces the breakdown voltage [18].

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Thus, the proposed method for determining the diameter of microplasmas makes it possible to reliably determine this key parameter according to differential characterography data (breakdown voltage and differential resistance of microplasma) and, accordingly, the parameters of current filaments, which plays an important role in diagnosing the reliability of semiconductor diodes operating in the avalanche breakdown mode.

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