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RESEARCH OF AVALANCHE BREAKDOWN OF P-N JUNCTIONS

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SUMMARY

The perfection of the source material, at the same time, very much depends on the technological processing methods used. Dislocations in the crystal structure are generated due to the occurrence of internal stresses, leading to plastic deformation of the material. Numerous studies have shown that one of the main causes of degradation and failure of semiconductor devices is the presence of internal mechanical stresses in them, the relaxation of which is accompanied by the appearance of structural defects.

KEY WORDS: *avalanche breakdown, microplasma breakdown, light emission, cylinder shape.*

1. INTRODUCTION

The reliability of semiconductor devices is primarily determined by the degree of perfection of the source material at the same time, and very much depends on the technological processing methods used. Obtaining films on a single-crystalline substrate or epitaxial growth makes it possible to introduce a dopant with an arbitrary required concentration and obtain a p-n junction, avoiding the process of solid-phase diffusion. This is due to the fact that the degradation of almost all devices is based on the phenomena of diffusion, defect formation and decomposition of supersaturated solid solutions [1].

In devices containing p-n junctions with high impurity concentration gradients, degradation of parameters will be observed over time, associated, for example, with the spreading of concentration profiles due to diffusion [2]. Taking into account all the factors that appear during the operation of devices, knowing the diffusion coefficients of impurities, it is possible to determine the amount of deformation of the concentration profile and predict the degree of degradation of electrical characteristics associated with changes in the profile [3Analyzing these processes, the process of avalanche breakdown of real large-area p-n junctions, which has a microplasma character, remains poorly studied. Indeed, already in the very first studies of avalanche breakdown of p-n junctions and Schottky diodes, it was shown that the breakdown in them is highly localized [4].

The local breakdown region has small geometric dimensions and a significantly lower breakdown voltage compared to homogeneous regions. The region of such localized breakdown was called microplasma [Mp]. However, [5-6] it was shown that dislocations do not always cause the appearance of microplasmas. p-n addition, in [7] it was theoretically proven that the phenomenon of microplasma breakdown can be interpreted as a special type of instability that occurs even in the case of an ideal p-n junction. In addition, analysis of experimental data shows that a local decrease in the breakdown voltage is most likely promoted not by single dislocations, but by their clusters.

2. EXPERIMENTAL SAMPLES

Experiments on silicon p-n junctions have revealed that the effect on the impact ionization current during an avalanche breakdown of inhomogeneous heating of a semiconductor is fundamentally different from the case of uniform heating. The temperature gradient, depending on the direction relative to the current, can either effectively (more strongly than with uniform heating) reduce or increase the impact ionization current. In this case, the breakdown voltage of the p-n junction changes significantly. The results obtained are explained by theory [8], which takes into account that, under the realized conditions, the flow of electric current leads to an increase or decrease in the number of electron-hole pairs in the space charge region of the p-n junction.

According to the theory of these phenomena [8], heating the p-n junction reduces the impact ionization coefficients of electrons and holes, which results in a decrease in the impact ionization current and an increase in the breakdown voltage of the p-n junction. These results are confirmed by experiments in which p-n junctions were heated uniformly.

We investigated impact ionization and avalanche breakdown in inhomogeneously heated p-n junctions. It was found that the effect of such heating on the current is fundamentally different from the case of uniform heating. The temperature gradient, depending on the direction relative to the current, can either effectively (more strongly than with uniform heating) reduce or increase the impact

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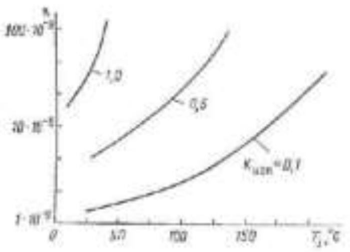
ionization current. In this case, the breakdown voltage of the p-n junction changes significantly. The existing theory of impact ionization does not even qualitatively explain the experimental results obtained.

This stimulated the development of the theory of breakdown of a pn junction located in a nonuniform temperature field. This theory was developed in [9] and with its results the experimental results of this work are compared. Since the threshold ionization energy is proportional to the band gap width, elastic deformation leads to an increase in the local ionization coefficient. Other factors that lead to a decrease in avalanche breakdown voltage are also associated with dislocations, since dislocations are centers of deposition and increase the diffusion coefficients of impurities, which can lead to a local narrowing of the space charge region (SCR). In [10, 11], dislocations, point defects in silicon and associated localized energy states, as well as kinetic phenomena in deformed Si crystals, were studied.

Taking into account the above, it can be argued that the role of dislocations in the occurrence of microplasma breakdown is not fully understood. We studied p-n junctions with a breakdown voltage of 12V; at room temperature, the appearance of the first microplasma causes a current jump or fracture in the current-voltage characteristic. In the voltage range of the phenomenon of the first microplasma, no other microplasmas appeared in its vicinity.

Microplasma radiation using an optical system built on the basis of a vertical microscope for high temperatures.



Rice. 1 Dependence of the failure rate of semiconductor devices on the temperature of the structure [12]

The curves in Fig. 1 show how the failure rate of semiconductor devices changes with increasing structure temperature: already at a temperature of about 100°C, the reliability of the devices decreases by 5-10 times compared to the reliability at a temperature of 25°C [12]. If at the same time the device is simultaneously used to the maximum in any electrical parameter, then the failure rate can increase 100 times or more.

3. CALCULATION RELATIONS: SIMULATION OF 3-DIMENSIONAL CONTINUOUS RANDOM DEFECTS AT A P-N JUNCTION WITH ARBITRARY COORDINATES USING THE MONTE CARLO METHOD

In diol p-n junctions we denote all points with the letter ξ1,..., ξn are dependent, their joint density can be represented as the product of the conditions of the probability densities of these quantities: $P_Q(x_1, \dots, x_n) = P_1(x_1)\, P_2(x_2 \mid x_1)\, P_3(x_3 \mid x_1, x_2) \dots P_n(x_n \mid x_1, \dots, x_{n-1})$. All conditional probability densities are expressed through the joint density $P_n(x_1, \dots, x_n)$. We present expressions for conditional densities in general form; all integrals are taken from -∞ to +∞ let' s define the first defect $P_1(x_1) = \int \dots \int P_Q dx_2 \dots dx_n$, second defect $P_2(x_2|x_1) = \int \dots \int P_Q dx_3 \dots dx_n, [P_1(x_1)]^{-1}$
third defect $P_3(x_3|x_1, x_2) = \int \dots \int P_Q dx_1 \dots dx_n, [P_1(x_1) P_2(x_2|x_1)]^{-1}$,
n-1st defect$P_{n-1}(x_{n-1}|x_1, \dots x_{n-2}) = \int P_Q dx_n, [P_1(x_1) \dots P_{n-2}(x_{n-2}|x_1 \dots x_{n-3})]^{-1}$,
we define the nth defect$P_n(x_n|x_1, \dots x_{n-1}) = P_Q [P_1(x_1) \dots P_{n-1}(x_{n-1}|x_1 \dots x_{n-1})]^{-1}$
In the form of conditional definitions of distribution function defects$F_i(x_i|x_1, \dots x_{i-1}) = \int_{-\infty}^{x_i} P_i(x|x_1 \dots x_{i-1}) dx$. Let γ1, …, γn be independent random numbers, which we will define as a random defect. A set of random variables ξ1,…, ξn obtained by sequentially solving equations with the system

$$F_1(\xi_1) = \gamma_1$$

$$F_1(\xi_2 \mid \xi_1) = \gamma_2$$

,,,,,,,,,,,,,,,,,,

$$F_n(\xi_n|\xi_1, \dots, \xi_{n-1}) = \gamma_n$$

At each coordinate there are silicon atoms or either electrons and holes, defects. We have determined the functions of defects located at the p-n junction. If we prove that these defects located at the p-n junction, the values ξ1= x1, …, ξ i-1= xi-1 are fixed, then we

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denote the random variable ξ 1 with the distribution function as F_i (ξ _i | x_1,⋯, x_(n-1))= γ _i. Then the definition of defects probability in the inequality x1< ξ 1< xi+dx is equal to P {x_ (i)< ξ _ (i)<x_(i)+dx_(i) |x_(i-1) }=P_i (x_i |x_i, …,x_(i-1))dx

Consequently, with the accuracy of determining the defect to infinitesimals of a higher order, the probability of joint fulfillment of the inequalities is equal to the product $P\{x_1 < \xi_1 < x_1 + dx_1, \dots, x_n < \xi_n < x_n + dx_n\} = P\{x_1 < \xi_1 < x_1 + dx_1\}P\{x_2 < \xi_2 < x_2 + dx_2 \mid \xi_1 = x_1\} \dots P\{x_n < \xi_n < x_n + dx_n \mid \xi_1 = x_1, \dots, \xi_{n-1} = x_{n-1}\} = P_1(x_1)dx_1P_1(x_1)dx_1P_2(x_2|x_1)dx_2 \dots P_n(x_n|x_1, \dots, x_{n-1})dx_n = P_Q(x_1, \dots, x_n)dx_1 \dots dx_n$. and the definition of the defect is proven. Using the geometric Monte Carlo method, we will determine the volume of microplasma based on its cylindrical shape. Let's mark the volume of space charge at the p-n junction with the letter Vopz. In this area we find a defect with which means microplasma. At this coordinate, we note the appearance of microplasma functions f(P) where located in the segment 0⩽ f(P) ⩽ h. In the three-dimensional space x, y, z, consider the cylindrical region $V_{mp}=V_{scr}\times(0, h)$, and in the microplasma volume V_{mp}, consider a random height point of the microplasma coordinate zh with density $\bar{\bar{P}}(x, y, z) = \frac{1}{h}P(x, y)$.

Obviously, the projection of the point z_h on the x, y planes where the defect that affected the microplasma is located is a random point h=(x, y), and the third coordinate h, let's call it z, does not depend on x and y and is uniformly distributed in the interval 0< z<h, so that its density P_z (z)=1/h we choose N independent realizations h1, h2, …, hn of the random point h; Let us denote by ν the number of points that are below the surface z=f(P) and make an estimate (Θ_N)¯=(h×ν)/N. The discrete random variable ν obeys the Bernoulli distribution P{ ν =m}=h_N^m P^m 〖(1-P)〗^(N-m) (m=0,1,⋯N), where P is the probability that the point h will be below the surface of the microflame z=f(P) .

Let's calculate this probability: $P = P\{h_{мп} < f(x_{мп}; y_{мп})\} = \int_{V_{мп}} dxdy \int_{\theta}^{f(x,y)} \bar{P}(x, y, z)dz = \frac{1}{h}I$. because $M\nu = N_p = \frac{1}{h}NI$, then from $\overline{\Theta_N} = \frac{h\times\nu}{N}$ it follows that $M\overline{\Theta_N} = I$. Convergence $\Theta_N \xrightarrow{P} I$ follows from the well-known Bernoulli theorem on the convergence of frequencies to probabilities. However, the estimate from$\overline{\Theta_N} = \frac{h\times\nu}{N}$ тacan also be represented in the form $\overleftarrow{\xi_N} = \frac{1}{N}\sum_N^1 \xi_i$. Absolute convergence of the integral I= $\int_{scr} f(P)P(P)dP$ follows from the limitation 0≤ f(P) ≤ h. .

The geometric method is a generalization of the method for calculating the volume of microplasma where the defect is located in the space charge region. if the SCR volume is limited then we solve it like this $P(\mathrm{P}) \equiv \frac{1}{S_{scr}}$ at $P \in V_{scr}$, then for large N numbers it is equal to $\frac{\nu}{N} \approx \frac{I}{h} = \frac{V_{MP}}{V_{scr}}$ where $V_{MP} = \int_{V_{scr}} f(P)dP$ volume of part space charge region V_{scr} , microplasma wire limited at the top by a cord surface$z = f(x_{мп}; y_{MP})$ and the volume of microplasma is equal to$V_{MP} = h \cdot S_{MP}$ this is the volume of the entire cylindrical region of the mycoplasma.

4. METHODOLOGY OF EXPERIMENTAL RESEARCH

Breakdown of a semiconductor diode most often occurs primarily through local areas where there are significant field distortions in the SCR, arising due to various types of defects, or associated with inhomogeneity of doping. Such areas are called microplasmas (MP). Accordingly, the degradation of semiconductor devices operating in the breakdown region is determined to a greater extent by the thermal properties of the MF. The study of the thermal properties of microplasmas is possible by measuring the noise characteristics of microplasmas, the method of modulation differentiation, as well as some optical methods. Measurement of noise microplasma characteristics.

Turning on the MF is accompanied by the appearance of jumps or bends in the current-voltage characteristic, as well as high-frequency noise when the MF is turned on and off. (Fig. 1a).

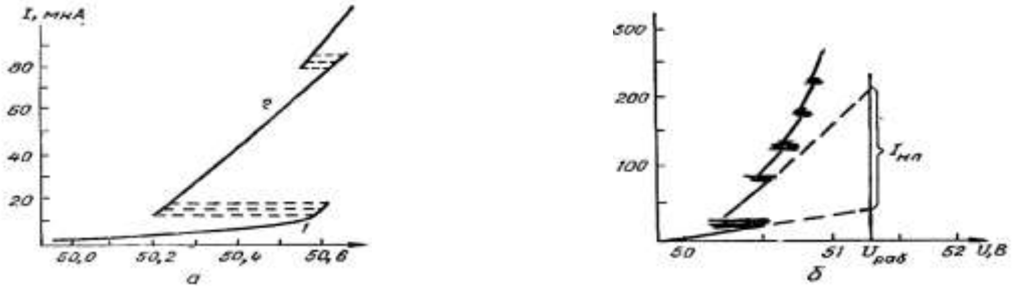

Fig.-1 Typical view of the reverse branch of the current-voltage characteristic of a diode with microplasmas (a), section of the current-voltage characteristic with an enhanced high-frequency noise component (b), [13] 1-section preceding the switching on of the first MF, 2-section with the switching on of the first MF. The dashed lines show transitions from 1 and 2 when the MP is turned on and from sections 2 and 1 when the MP is turned off.

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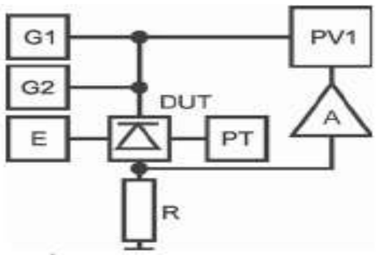

Fig.2. Block diagram of a microplasma characterograph: G1-direct current source; G2 sawtooth current generator; DUT-connecting device with diode; PV1-oscilloscope with recording device; A-Selective amplifier; RT case temperature meter; E-heater

The amplitude of microplasma noise characterizes the magnitude of the voltage jump between sections 1 and 2; therefore, information about the magnitude of this jump can be extracted from the noise characteristics of the current-voltage characteristic.

To study microplasma noise, a microplasma curve tracer is used, the block diagram of which is shown in Fig. 2 [13]. The operation of the characterograph is based on the fact that microplasma noise has components with a frequency above 100 kHz, which makes it possible to separate it from the constant component. Current flows through the DUT diode under study from the sawtooth current generator G2 and the direct current source G1, and the voltage drop across the diode through amplifier A is supplied to the input of oscilloscope 4, synchronized with generator 1.

The amplifier has unity gain at frequencies below 50 kHz and variable gain at frequencies above 50 kHz and variable gain at frequencies above 50 kHz, which ensures that only high-frequency noise is amplified. Microplasma characterograph: differential resistances, currents flowing through the MP in operating mode, diameters of hot areas and their temperatures. Using these parameters, it is possible to sort diodes and predict uptime.

The differential resistance of the i-th MF $R_{Дi}$ is determined by the slope of the linear section of the current-voltage characteristic. If R_{di}-1, R_{di} are the differential resistances of successive linear sections of the current-voltage characteristic, then the resistances of the corresponding MPs are equal to:

$$R_{МПi} = \frac{R_{Дi-1}R_{Дi}}{R_{Дi-1}-R_{Дi}}10^9 \quad (1)$$

The current flowing through the MP in operating mode can be found by extrapolating the corresponding section of the current-voltage characteristic to the operating voltage of the diode. The differential resistance of the MF can be represented as the sum of three components: $R_{MP} = R_C + R_{OSC} + R_t$, where R_C is the spreading resistance, RSC is the resistance of the space charge region, Rt is the thermal component of the resistance. $R_C = \frac{\sqrt{2}\cdot\rho}{\pi\cdot d_{мп}}$

where , $\rho = \frac{1}{e\cdot\mu_n\cdot n}$ - resistivity of the quasi-neutral region of the semiconductor;

μ – carrier mobility, d_{mp} - microplasma diameter,
n – concentration of free charge carriers.
SCR resistances can be found using the approximate formula:

$$R_{SCR} = \frac{L_{MP}}{\pi\varepsilon_S\upsilon_S d_{MP}} \quad (2)$$

Where ε_S is the dielectric constant of the semiconductor, and υ_S is the saturated drift velocity of carriers in the semiconductor, L_{MP} is the length of the MP. The thermal component of the MF resistance largely depends on the material and design features of the diode. If the multiplication region is removed from the metal heat sink, then R_t- can be found from the expression

$$R_t \simeq \frac{0{,}07\cdot B\cdot V_{МП}^2}{k\cdot L_{МП}}\left[4\cdot\sqrt{\frac{L_{МП}}{d_{МП}}}\ -1\right] \quad (3)$$

where B is the temperature coefficient of diode breakdown voltage, k is the thermal conductivity coefficient, V_{MP} is the breakdown voltage of the MP. As you can see, R_t significantly exceeds R_s and R_{SCR}. Based on this, using the formula

$$R_t \simeq \frac{0{,}07\cdot B\cdot V_{MP}^2}{k\cdot L_{MP}}\left[4\cdot\sqrt{\frac{L_{MP}}{d_{MP}}}\ -1\right]$$

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find d_{mp} and determine overheating

$\Delta T_{\text{МП}} = I_{\text{MP}} \frac{R_t}{B \cdot V_{\text{MP}}}$ (4) . Using these data, it is possible to reject diodes with the hottest MPs and predict the life of the diodes.

Measurement of derivative current-voltage characteristics. The presence of nonlinearity in the diode's current-voltage characteristic may indicate a change in the mechanism of current flow, the inclusion of an MP, or a violation of the uniformity of current flow.

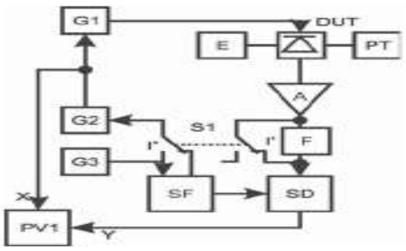

Fig. 3. Block diagram of the characteristic graph for modulation differentiation (CVH) [14].

Weak changes in the current-voltage characteristics associated with these nonlinearities are poorly diagnosed from static current-voltage characteristics, but are easily visible on their derivatives, which makes it possible to determine the rate of degradation processes and predict diode failures. There are several methods for measuring derivatives of the current-voltage characteristics, including numerical differentiation of the current-voltage characteristics and differentiation using modulation with sinusoidal or linearly varying voltages. Modulation methods are usually preferred because they are placed higher up.

The essence of the method for measuring derivatives of current-voltage characteristics with sinusoidal modulation is to measure the parameters of a filtered alternating current signal through a diode, to which a modulating sinusoidal signal is applied in combination with the bias voltage.

The block diagram of modulation studies of microplasma breakdown is shown in Fig. 3. It includes a series-connected scan generator G_1, a constant bias source G_2, an audio frequency modulation generator G_3, which forms a signal source block. The I0 value is set slightly below the start of the breakdown. The sweep to the section of the current-voltage characteristic that interests us is carried out by a sweep generator. The sample current is measured by the operational amplifier after processing using a synchronous SD detector and is used to plot differential dependence graphs.

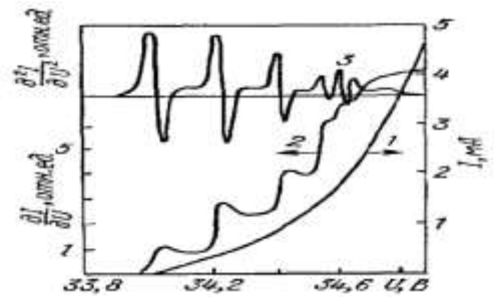

Fig. 4. Breakdown section of the current-voltage characteristic of a Schottky diode (1) and the curves of the first (2) and second derivatives (3), obtained on a modulation characterograph [14].

In the case where the first derivative is measured, the bias voltage is modulated by a double-frequency signal. To obtain the second derivative, the mixing voltage is modulated by the frequency of the first harmonic.

Voltage modulation leads to width and frequency modulation of microplasma pulses, which forms an alternating output signal, the harmonics of which are proportional to the derivatives of the current-voltage characteristics of individual MPs. Since the breakdown section of the current-voltage characteristic is formed by a set of MFs that are sequentially turned on as the bias current increases, the graph of the first derivative of the current-voltage characteristic turns out to consist of individual steps (Fig. 4.).

Based on the height of the steps, it is possible to determine the conductivity of each individual MP and calculate the thermal parameters of the MP, similar to measurements of noise microplasma characteristics. Based on the appearance of the second derivative of the current-voltage characteristic, one can detect the formation of a hot spot and estimate its diameter and temperature.

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Thus, monitoring the thermal parameters of high-power semiconductor devices is one of the main ways to predict individual failure-free operation. The choice of method and equipment for monitoring the thermal parameters of semiconductor devices depends on the production stage, the type of packaging of the semiconductor device and its operating mode.

5. EXPERIMENTAL RESULTS AND DISCUSSION

In the experiments, simultaneously with the observation of the current-voltage characteristic of the p-n junction, the intensity of light emission of a separate microplasma was measured. To observe the current-voltage characteristic, a microplasma curve tracer was used. Areas with a current-voltage characteristic were observed, which made it possible to determine the absolute values of the electrical parameters of the microplasma by a “jump” in the current or a break in the current-voltage characteristic.

The maximum light intensity can be taken as the limit separating the area of avalanche breakdown with increasing voltage and light intensity from the area of thermoelectric breakdown with decreasing light intensity with increasing voltage. On the side of high voltages, the region of thermoelectric breakdown of microplasmas limits the appearance of negative dynamic resistance of the secondary breakdown of the p-n junction.

6. CONCLUSION

It was found that an increase in the reverse bias voltage leads to an increase in the intensity of the output pulse flux at the output of the noise diode. It was revealed that at high intensity values of the output pulse flux, for all studied brands of noise diodes, the presence of correlations between the pulses was observed. It has been established that the dependence of the intensity of the output pulse flow on the magnitude of the current flowing through the noise diode has two sections in which this dependence is linear. Thus, based on the analysis of the obtained dependencies and characteristics, we can conclude that the following processes occurring in noise diodes affect the intensity of the pulse flux at their output: impact ionization of minority charge carriers leaving the space charge region; thermal generation of charge carriers.

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