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DIFFERENTIAL RESISTANCE TO ALTERNATING CURRENT DURING BREAKDOWN OF CURRENT IN DEEP LEVELS IN A SILICON P-N JUNCTION

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SUMMARY
The current-voltage characteristic, the dependence of the nonmonotonic temperature on the differential resistance, and the change in the sign of the temperature coefficient depend on the change in the breakdown voltage. The change in the sign of the temperature coefficient is associated with the charging of the space charge region in the p-n junction, which occurs in the deep level. Because of the avalanche breakdown in silicon, the charge change in the deep level has a strong effect on increasing and decreasing the probability of microplasma formation. Measuring the possibility of turning on microplasma without filling deep centers makes it possible to obtain information about the mechanism of creation of charge carriers in microplasma channels of the p-n junction.
KEY WORDS: *deep levels, avalanche breakdown, temperature coefficient*

Recently, in [2], new interesting phenomena were described that are observed during the breakdown of electron-trained silicon p-n junctions. If the concentration of the deep center is low, then they affect the statistical delay in the breakdown of microplasmas [3]. It has been shown that, when the charge state of the deep center changes by a partial decrease in the voltage at the p–n junction, the statistical delay of microplasma breakdown makes it possible to estimate the energy spectrum of deep levels localized in the microplasma channel at their low concentration, when other methods are inapplicable [4]. When studying the nonmonotonic dependence of temperature on the differential resistance of the Rd microplasma, it turns out that the change in the sign of the temperature coefficient depends on the breakdown of the alternating current and the concentration Up. The change in the temperature coefficient is explained by the authors in scientific papers [5]. In the p-n junction, the space charge is charged in deep layers. As a result of the growth of an infinitely thin layer at a constant temperature, Rt appears - a negative value of the temperature component of the resistance on the voltmeter characteristic [6].
In this approximation, the maximum field strength Em after breakdown is constant (Em=Eb=const) and almost in the entire space charge region (SCR). If p=0 ; $n = \frac{j}{q \cdot v_n}$

$$\rho(x) = q \cdot |N - n - N_i \cdot f_n| \qquad (1)$$

Где j – плотности тока, v_n - дрейфовая скорость электронов. Используя известное соотнощение между U напряжения , ρ и максимальная напряженность поля $E_м$ для резкого перехода получим ВАХ после пробоя в виде

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Where j is the current density, is the drift velocity of electrons. Using the known relationship between voltage U , ρ and the maximum field strength E_m for a sharp transition, we obtain the CVC after breakdown in the form

$$U = U_{breakdown(o)} \frac{N}{N-n-N_t \cdot f_n} \qquad (2)$$

The index 0 (zero) hereinafter refers to the values corresponding to the zero filling of the deep level. In the nth layer, the space charge region (SCR) can be recharged with a change in current or temperature only at a deep level located in the upper half of the charged band, for which, when the number of donors is greater than the number of acceptors

$$n_1 = \frac{a_n}{b_n} = N_e \cdot exp(-\frac{E_i}{k \cdot T}) \qquad (3)$$

Ne is the effective density of states, Ei is the ionization energy of a deep level. The main role in the study of the functions of diodes of an avalanche diode [7] is played by a theoretical study of the variability of bulk breakdown in a p-n junction, and the differential resistance of a microplasma is expressed in terms of R_d. As is known [7], in general case, the value of the differential resistance of the microplasma R_D can be written as the sum

$$R_Д = R_0 + R_c + R_t \qquad (4)$$

where R_0 is the spreading resistance,
Rc - resistance (SCR) space charge region,
R_t is the thermal component of the microplasma resistance.
According to [7], the value of R0 can be calculated by the formula:

$$R_0 = \frac{\sqrt{2} \cdot \rho}{\pi \cdot d_{мп}} \qquad (5)$$

where ρ = - specific resistance of the base;
μ is the carrier mobility,
d_{mp} - microplasma diameter,
n is the concentration of free charge carriers.
the second resistance is the space charge region (SCR) in the p-n junction of silicon:

$$:R_c = R_{co} \left[\frac{(1+\gamma) \cdot j + j_1}{\lambda \cdot j + j_1}\right]^2 \qquad (6)$$

In that $R_{co} = \frac{\omega_{bo}^2}{2 \cdot \varepsilon \cdot \varepsilon_0 \cdot v_n \cdot S} = \frac{\omega_{bo}^2}{2 \cdot \varepsilon \cdot \varepsilon_0 \cdot v_n \cdot \frac{\pi \cdot d_{мп}^2}{4}} = \frac{2\omega_{bo}^2}{\pi \cdot \varepsilon \cdot \varepsilon_0 \cdot v_n \cdot d_{мп}^2}$

- this U=Ubreakdown (o) - the width of the space charge region. S is the cross-sectional area of the microplasma.
The value of Rt, taking into account the variability of heat release in the p - n junction, is determined as:

$$R_t = \frac{2 \cdot \beta \cdot \varphi_{мп}^2}{\pi \cdot \lambda \cdot d_{мп}^2 L} \cdot \left\{ \left(1 - \frac{X_0}{L}\right) \left[z\sqrt{z^2 + R_{мп}^2} + R_{мп}^2 \cdot l_n \left(z + \sqrt{z^2 + R_{мп}^2}\right) - |z|z \right] - \frac{2}{3L} \left[\left(z^2 + R_{мп}^2\right)^{\frac{3}{2}} - |z|^3 \right] \right\}_{-X_0}^{L-X_0} \qquad (7)$$

where: - - coefficient of thermal conductivity of the semiconductor,
mp - microplasma breakdown voltage,
- temperature coefficient of breakdown voltage,

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L is the length of microplasmas [8].

The temperature of the microplasma channel in comparison with the ambient temperature is determined by the expression:

$$\Delta T_0 = \Delta T_1 + \Delta T_2 = \frac{R_{T1}\cdot \Delta J}{\beta\cdot \text{Uмп}} + \frac{R_{T2}\cdot \Delta J}{\beta\cdot \text{Uмп}} \qquad (8)$$

Where Ump is the microplasma breakdown voltage;

RT_2, ΔT_2 - thermal component of the diode resistance and its heating as a whole;

RT_1, and ΔT_1 are the corresponding values for the microplasma channel.

The value of ΔT0 allows us to determine from $\Delta T_0 = \Delta T_1 + \Delta T_2 = \frac{R_{T1}\cdot \Delta J}{\beta\cdot \text{Uмп}} + \frac{R_{T2}\cdot \Delta J}{\beta\cdot \text{Uмп}}$ temperature of the microplasma channel, RT2 is easily determined from the thermal resistance known from the experiment

$$R_{T2} = \beta U_m^2 r_{T2} \qquad (9)$$

In the experiment, the value of the total series resistance is found, which, in addition to

$$R_T = R_{T1} + R_{T2} \qquad (10)$$

includes the spreading resistance R0 and the SCR resistance Rc , and it is difficult to determine RT experimentally .

In view of the nonmonotonic temperature dependence of the differential resistance of the microplasma Rd , at low temperatures T the differential resistance of the microplasma is calculated depending on the temperature T and the current density j.

The first is the corresponding values for the microplasma channel

$$R_{T1} = R_{co}\frac{j_t\cdot j_1}{(\lambda\cdot j + j_1)^2}\left[1 - \frac{j\cdot r_T\cdot U_{bo}}{T}\left(\frac{E_{KT}}{k\cdot T} + \frac{3}{2}\right)\right] \qquad (11)$$

Second term

$$R_{T2} = R_{TO}\left[\frac{(1+\gamma)\cdot j + j_1}{\lambda\cdot j + j_1}\right] \qquad (12)$$

heating device.

Where $R_{co} = \frac{\omega_{bo}^2}{2\cdot\varepsilon\cdot\varepsilon_0\cdot\nu_n\cdot S} = \frac{\omega_{bo}^2}{2\cdot\varepsilon\cdot\varepsilon_0\cdot\nu_n\cdot\frac{\pi\cdot d_{\text{мп}}^2}{4}} = \frac{2\omega_{bo}^2}{\pi\cdot\varepsilon\cdot\varepsilon_0\cdot\nu_n\cdot d_{\text{мп}}^2}$

$$j_1 = q\cdot\nu_n\cdot n_1 \quad j_t = q\cdot\nu_n\cdot N_t \qquad \lambda = \left(1 + \gamma - \frac{N}{N_t}\right)$$

r_T - thermal resistance of the device

As the temperature rises, the GCs begin to empty, fn strongly depends on T and j, so R_d sharply increases and reaches its maximum value.

$$R_{\text{max}} = R_{\text{д}}(T) = R_{co}\frac{(1+\gamma+\lambda)^2 + \lambda\cdot j_t / j}{4\cdot\lambda^2} \qquad (13)$$

At a temperature

$$T = T_{\text{д}} = E_t\left[k\cdot\ln\frac{q\cdot\nu_n\cdot N_e}{\lambda\cdot j}\right]^{-1} \qquad (14)$$

При дальнейшем увеличени температуры скорость эмиссий намного превосходит скорост захвата, ГУ польностью о пустощаются и $R_д$ опять перерастает зависить от j и T [9].

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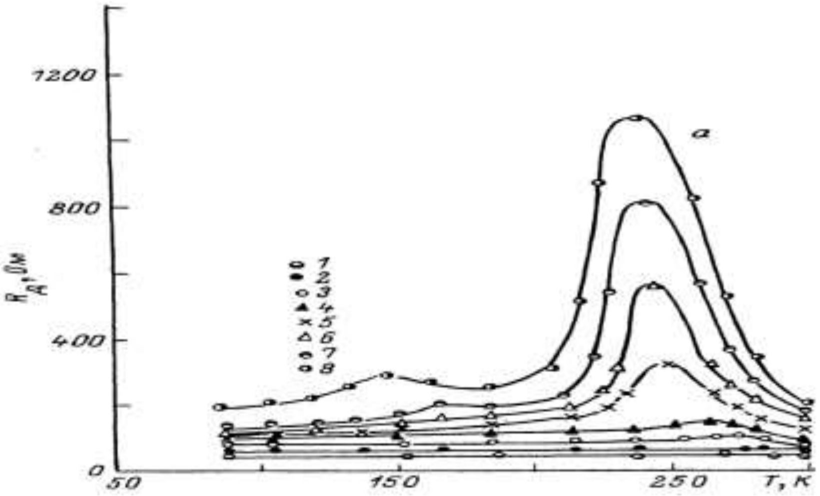
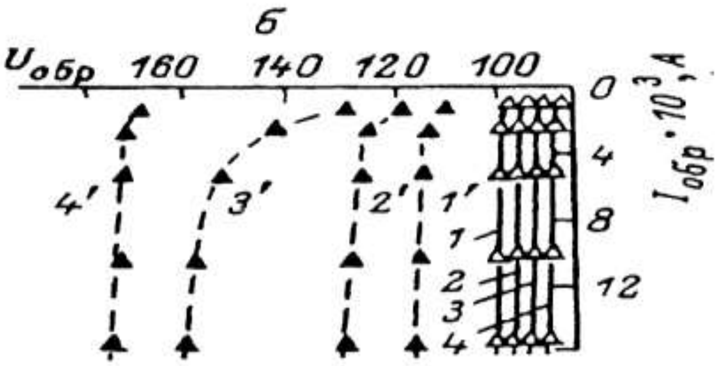
With a further increase in temperature, the emission rate far exceeds the capture rate, the BCs are completely emptied, and R_d again outgrows the dependence on j and T [9].



1-Fig. Temperature dependence of the differential resistance in the breakdown region of a silicon reverse p-n junction. Fluence radiation, Φ, cm -2 : 1 - up to radiation , 2 - 5•10^{15}, 3 - 1•10^{16} , 4 - 2•10^{16} , 5 - 3•10^{16} , 6- 5•10^{16} , 7- 4•10^{16} , 8-6-10^{16} [2].



2-Fig. VAX silicon p-n reverse junction [2].
1, 1' — 300 К;
2, 2' — 252 К;
3, 3' — 220 К;
4, 4' — 200 К.

In the vicinity of T=T_max, R_d strongly depends on the current and decreases with the value λ·j<<j_1, this decrease in R_d means "softening" of the CVC observed experimentally. Finally, at all temperatures and currents, Rd increases, and T decreases with increasing Nt in full accordance with the results of [2]. It is also interesting to note that at low temperatures and low currents, when the inequalities

λ·j<j_1<<j_t the presence of a GU can increase Rt much briefly even if . Speaking about the temperature dependence of U_b, we mean the voltage corresponding to a certain fixed value of the current, this dependence is fully described by the equations

$$\beta_t = \frac{1}{U}\cdot\frac{dU}{dT} = \beta_{To} - \frac{j\cdot j_1}{(\lambda\cdot j+j_1)[(1+\gamma)\cdot j+j_1]}\cdot\frac{N_t}{N}\cdot\left(\frac{E_t}{k\cdot T}+\frac{3}{2}\right)\cdot\frac{1}{T} \quad (15)$$

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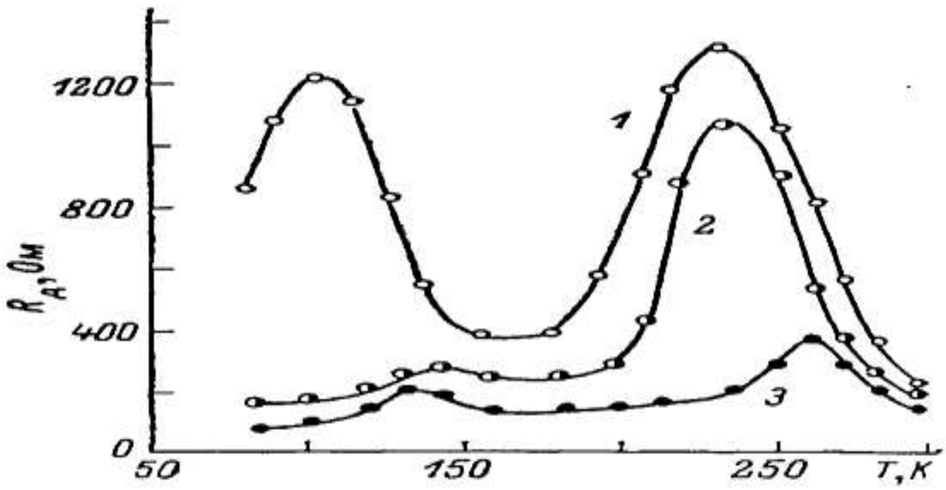
Where β_To=(1/U_bo)·((dU_bo)/dT) it is easy to make sure that at , an anomaly should be observed on the dependence, and the sign of β_T should even change if, 1/(2·(1+λ+γ)) ·N_t/N·E_g/(k·T)>β_To≅10^(-3)



K^(-1)

3-*Rice. Temperature dependence of differential resistance in silicon p-n junction at different temperatures [2].*

In the non-isothermal case, a significant Rd is the thermal component RT_1, but in low-voltage devices, taking into account self-heating does not give anything qualitatively new compared to the above, in high-voltage devices, the most interesting effect of self-heating is a strong change in the large “trap” resistance R_t. From

$$R_{T1} = R_{co}\frac{j_t \cdot j_1}{(\lambda \cdot j + j_1)^2}\left[1 - \frac{j \cdot r_T \cdot U_{bo}}{T}\left(\frac{E_{KT}}{k \cdot T} + \frac{3}{2}\right)\right] \quad \text{видно,что при } j \cdot r_{T.} \cdot U_{bo} > \frac{k \cdot T^2}{E_t}$$

the sign of Rt changes, therefore, in the vicinity of T=Tm, the Rd(T) dependence should show not a maximum, but a minimum. Moreover, if |R_t |> 〖R〗_T_1+R_T_2 , a section with negative differential resistance may form. This effect was observed earlier in [10-11] when studying high-voltage silicon p-n junctions. It is obvious that the presence of several types in the forbidden zone. GU, with different ionization energies should lead to the appearance of an appropriate number of maxima (or minima) in the dependence Rt(T) at temperatures, defined by the formula

$$T = T_Д = E_t\left[k \cdot \ln \frac{q \cdot v_n \cdot N_c}{\lambda \cdot j}\right]^{-1}$$

However, it should be noted that the contribution of different BCs to Rd is additive only at Nt<<N, since the thickness of the SCR ω_, on which R_d depends on the filling of all types of BCs.

However, it should be noted that the contribution of different BCs to Rd is additive only at Nt<<N, since the thickness of the SCR ω_, on which Rd depends on the filling of all types of BCs

Above, we did not explicitly assume that the quantities $n_1 = \frac{a_n}{b_n} = N_e \cdot exp(-\frac{E_i}{k \cdot T})$ и $\gamma = \frac{C_{nn}}{b_n}$ are constant throughout the SCR, and the equilibrium value was used for n1. In fact, in a strong p-n junction near breakdown, the rate of thermal generation increases due to the Pool-Frenkel effect or thermally stimulated tunneling [12–13]. The main consequence of this is the dependence of effective ionization energies. GU Et from the field, and hence from the coordinate. Therefore, the recharging of even one type of GU will occur in different SC_R currents at different temperatures. In addition, the field dependence will lead

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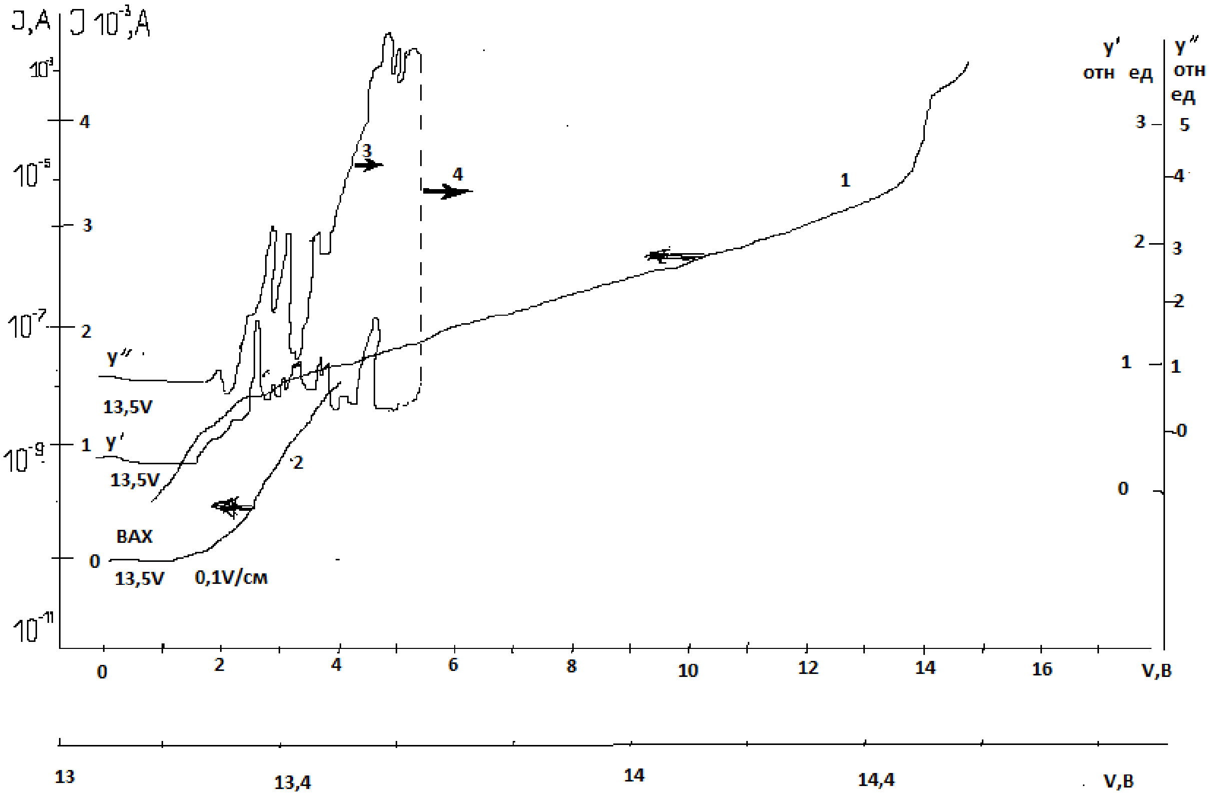
$\gamma = \frac{C_{nn}}{b_n}$ (если γ >>1) and non-uniformity of SCR temperature in high-voltage devices. Therefore, the width of the peaks in the Rd(T) dependence should be greater than what follows from the formula $R_{T1} = R_{co}\frac{j_t \cdot j_1}{(\lambda \cdot j + j_1)^2}\left[1 - \frac{j \cdot r_T \cdot U_{bo}}{T}\left(\frac{E_{KT}}{k \cdot T} + \frac{3}{2}\right)\right]$ according to which $T \equiv T_m(1 \pm 0{,}1)$. This circumstance makes it difficult to use the Rd(T) dependence; the number of DLs in the device is too small to be able to use capacitance spectroscopy [14].
This greatly affects the breakdown of the current in silicon to deep levels; A change in the charge of deep levels can also lead to an increase or decrease in the probability of the appearance of microplasma.



6-Fig. Typical junctions obtained by the method of modulating BAX differentiation in a silicon p-n junction [15].

From this process one can explore the deep center. As the temperature rises, the mean free path decreases due to an increase in the phonon concentration. Therefore, the required energy requires a large critical field at a shorter distance. Therefore, when the diode is heated, the avalanche breakdown voltage increases. The above results show that the analysis of the time dependence of cooling at different delay times for the relaxation of the alternating perturbation current (avalanche breakdown) makes it possible to determine the main parameter of deep levels - the thermal ionization energy [16–17]. This makes it possible to reduce the disadvantages of this phenomenon (it can be called microplasma spectroscopy of deep levels) associated with the filling of deep channels with breakdown current pulses. Analytical expression - the duration of the statistical delay of microplasma infection, the distribution function of the main parameters of deep cells. A method has been developed for determining the parameters of a deep center using the measurement of the statistical delay of microplasma recovery. Measuring the possibility of adding microplasma without filling deep centers allows obtaining information about the mechanism of creation of charge carriers in the microplasma channels of p-n junction silicon. Measurements at a voltage of 18-19V determine the tunneling mechanism for the entry of charge carriers into the microplasma channel.

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