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THERMAL MODEL OF THE LIMITER DIODE

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This paper considers thermal models of the voltage limiter in the regime of turning on and applying pulse voltage that permit determining the temperature of the depletion region of the p–n junction at any moment of the external pulse acting on the limiter diode, as well as the maximum temperature in the crystal.

Keywords: *limiter diode, temperature of the depletion region of the p–n junction, diffusion, heat flow, temperature potential, pulse.*

Introduction. In designing power semiconductor devices, it is necessary to take into account the possibility of a decrease in the temperature of the device itself under operating conditions whatever the electric field strength and the thermal conditions. The choice of reliable operating conditions requires knowledge of the thermal parameters of the semiconductor device determining the stability of operation and the maximum permissible powers and temperatures [1]. Such parameters as the *p–n* junction temperature, the heat resistance, and the heat capacity permit determining the dependence of the heating temperature of the structure and its corresponding regions on the current, voltage, and released power values. The power diode (in the given case the voltage limiter) is a multilayer system of heterogeneous elements adjoining one another with an internal heat source. The relationship between the thermal parameters is determined by the thermal model of a particular device.

For steady-state regimes [2], voltage limiters — stabilizer diodes whose ultimate permissible regimes and service conditions are impossible to predict — are used.

In the present paper, we propose models explaining the processes of heat transfer through the depletion region of the *p–n* junction and the depth of the limiter diode and present the results of calculations of the thermal regimes of voltage limiters depending on their ultimate permissible operating conditions.

Investigated Voltage Limiters. The investigated diodes were made by diffusion technology. As a base region, we chose *n*-type conductivity silicon with an initial thickness of 200 μm. The initial base silicon was preannealed and then, using IR drying, two boron layers and one phosphorous layer were deposited. The process of diffusion of impurities from the solid phase was carried out with the use of film-forming solutions of boron (SBC) and silicon phosphorous (SPC) compositions prepared on the basis of tetraethoxysilane and, accordingly, boric and phosphoric acids [3]. Thus, a p^+–n–n^+ structure with a cross-sectional area of 0.25 cm^2 was obtained. The thickness of the p^+ region was about 60 μm, and that of the n^+-type region was equal to 70 μm. On either surface, thermal compensators based on a copper disk of thickness 380 μm and diameter 0.33 cm are fused with the help of a 2–3 μm-thick silver solder at a temperature of 400°C. On either surface of the thermal compensators, Kovar layers of thickness 10 μm are applied. The limiter diode representing a multilayer system is schematically represented in Fig. 1.

Calculation of the Limiter Diode Model Depending on the Turning-on Regimes. *Reverse-biased regime.* If a sharply rising reverse current pulse is applied to the limiter diode, when in the reverse-biased regime, then as long as the diode voltage does not exceed the breakdown voltage, capacitive current will flow through the diode, and the electric field in all sections of the diode will grow at the rate [4]

$$\frac{dE}{dt} = \frac{j\,(t)}{\varepsilon\varepsilon_v}\,. \tag{1}$$

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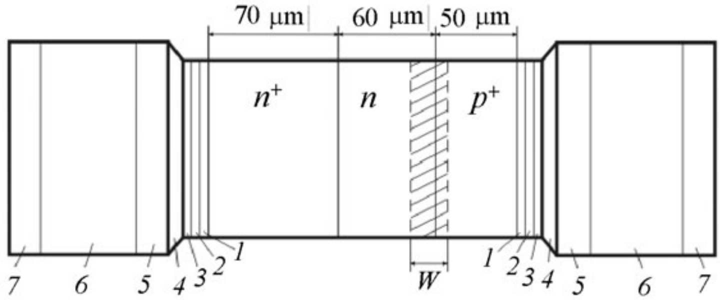


Fig. 1. Scheme of the n^+–n–p^+ silicon limiter diode: 1) deposited vanadium layer of thickness 0.1 μm; 2) deposited silver layer of thickness 0.1 μm; 3) silver layer applied by electroplating; 4) silver solder; 5, 7) covar layers; 6) copper disk.

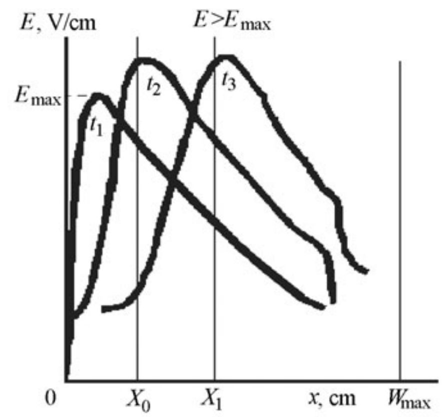


Fig. 2. Dependence of the electric field strength on the coordinate illustrating the shock wave propagation in the region of the p–n junction at various instants of time t_1, t_2, t_3.

The electric field will grow until at some point it reaches the breakdown value of E_{max}, after exceeding which avalanche multiplication of electrons and holes will occur. In this case, the current will increase so rapidly that the process of carrier drift can be neglected.

The region in which the field of $E > E_{max}$ moves rapidly (which causes shock wave propagation) is presented in Fig. 2. The slope of the curve $E(x)$ (t_2) to the right of the section $x = X_0$ is defined by the expression

$$\frac{dE}{dx} = \frac{q}{\varepsilon\varepsilon_v} N, \tag{2}$$

where N is the impurity concentration in the depletion region.

The shock wave velocity v_{sh} can be obtained by dividing relation (1) by (2), as a result of which we get

$$v_{sh} = \frac{dx}{dt} = \frac{j\,(t)}{qN}. \tag{3}$$

The maximum carrier velocity $v_s << v_{sh}$, but even under the condition that $v_s < v_{sh}$ the generated electron-hole plasma will have no time to scatter, as a result of which a shock wave will develop [4].

The obtained relations enable one to calculate the total turn-on time of the limiter diode t_{on} which will be composed of the time needed for charging the barrier capacitance of the p–n junction t_c as the voltage increases from the maximum voltage U_{max} to the breakdown voltage U_b with the initial current $I = jS$:

$$t_c = \frac{C\,(U_b - U_{max})}{I} = \gamma \frac{\varepsilon\varepsilon_v S}{W} \frac{E_{max} W}{2} \frac{1}{jS} = \gamma \frac{\varepsilon\varepsilon_v E_{max}}{j}\,, \tag{4}$$

where $C = \frac{\varepsilon\varepsilon_v S}{W}$, $\gamma = \frac{U_{max}}{U} \approx 0.01$, and the shock wave propagation time:

$$t_{sh} = \frac{W}{2v_{sh}} = \frac{qWN}{2j}\,. \tag{5}$$

It is necessary to add to these components the energy relaxation time $t_e \sim 10^{-12}$ s, i.e., the time needed for the energy to go from the carriers to the lattice. Then the total turn-on time of the limiter diode beginning from the moment at which the voltage pulse is applied is defined by the expression

$$t_{on} = \gamma \frac{\varepsilon\varepsilon_v E_{max}}{j} + \frac{qWN}{2j} + t_e\,. \tag{6}$$

Accordingly, after the appearance of the shock wave the heat transfer dynamics is largely determined by the turn-on circuit determining the current density *j*. At the end of the pulse the diode is turned off. This time is determined by the duration of dispersal of the electron-hole plasma generated in the depletion region. On the basis of formula (6) for the turn-on time t_{on}, going to the current *I* and neglecting the energy relaxation time t_e, we find the expression

$$t_{on} = \frac{1}{I}\left(\gamma\varepsilon\varepsilon_v E_{max} + \frac{1}{2} qWN\right) S = \frac{q_{on}}{I}\,. \tag{7}$$

Substituting relation (7) into the expression for the released thermal energy $Q_{n-p^+} = \frac{Pt_{on}}{2} = \frac{I^2 R t_{on}}{2}$, we get

$$Q_{n-p^+} = \frac{1}{2} IR q_{on}\,, \tag{8}$$

$$q_{on} = \left(\gamma\varepsilon\varepsilon_v E_{max} + \frac{1}{2} qWN\right) S\,. \tag{9}$$

The value of q_{on} is determined by only the material and design of the limiter diode. From the formulas $Q_{n-p^+} = (T_{n-p^+} - T_{ext})c\rho V$ and (8) it follows that the temperature of the *p–n* junction depletion region after the turn-on is determined by the expression

$$T_{n-p^+} - T_{ext} = \frac{I^2 R t_{on}}{2\rho c V} = \frac{I^2 R_{ohm} t_{on}}{2C_t} = \frac{IR q_{on}}{2C_t}\,. \tag{10}$$

The dependence of the temperature rise at the beginning of turning on the diode power is determined by the derivative $d\Delta T/dt$. Differentiating expression (10), we get

$$\frac{d\Delta T}{dt} = \frac{T_{n-p^+} - T_{ext}}{t_{on}} = \frac{I^2 R}{2C_t} = \frac{P}{2\rho c V} = \frac{P}{2C_t}\,. \tag{11}$$

From Eq. (11) it follows that the rate of temperature rise in the initial part of the turn-on is determined by the specific heat capacity *c*, the density of the material ρ, and the power density in the depletion region $p_f = P/V$. The effective thermal resistance in this region, by definition, will be [1, 5]

$$R_t = \frac{T_{n-p^+} - T_{ext}}{P} = \frac{I^2 R_{ohm} t_{on}}{2C_t P} = \frac{t_{on}}{2C_t} = \frac{q_{on}}{2C_t I}\,, \tag{12}$$

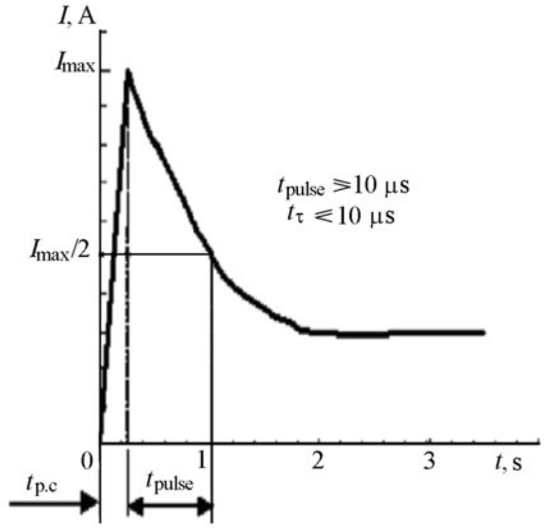


Fig. 3. Time dependence of the external generator current.

where the time constant $t_{on} = 2R_tC_t$ depends on the generator current ($t_{on} = q_{on}/I$).

At a generator voltage $U_{max} = U_b$ (see relation (4)) the thermal resistance becomes equal to

$$R_t^1 = \frac{q_{on}}{2C_tI} = \frac{Rq_{on}}{2C_tU_b}, \tag{13}$$

i.e., it is totally determined by the internal resistance of the generator R and the diode design since $q_{on}C_TU_b$ = const. In this part of $U_{max} \geq U_b$, the R_T value does not depend on the current and time.

Static regime. In the static case, in the depletion region one and the same quantity of heat is released per unit time. Therefore, the thermal flow dQ/dt is constant and equal to the electric power P:

$$\frac{dQ}{dt} = P = \text{const}. \tag{14}$$

Regime of turning on the diode. In the regime of turning on the diode, the input power P is determined by the external generator current I and its internal resistance R:

$$P = I^2R. \tag{15}$$

The thermal energy released in the diode is equal to

$$Q_{n-p^+} = \frac{Pt_{on}}{2} = \frac{I^2Rt_{on}}{2}. \tag{16}$$

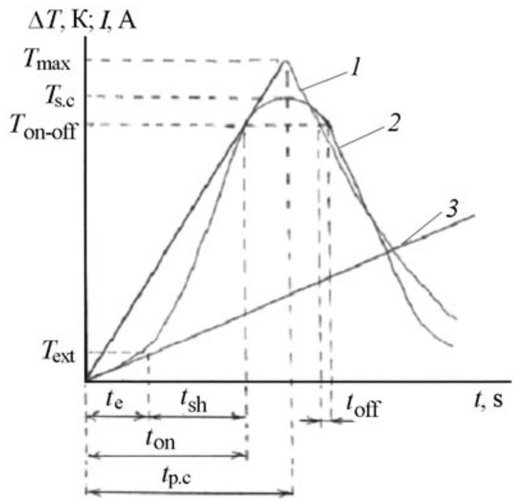
The rate of decrease in the temperature of the *p–n* junction depletion region is higher thereby than the rate of decrease in the current since the time constant of the thermal process $\tau_{max} = \tau_{pulse}/2$.

If for the turn-on time t_{on} we make use of expression (7), according to formula (10), taking into account that the current is a time function for the temperature increment, we obtain

$$\Delta T = T_p - T_{ext} = \frac{I(t)\,Rq_{on}}{2C_t},$$

where the temperature potential T_p consists of the sum of the temperatures before the action of the pulse and under the action of the pulse $T_p = T_{ext} + \Delta T$.

In the exponential section of the standard current pulse (Fig. 3) from the generator applied to the investigated diode, the temperature potential is determined by the relation



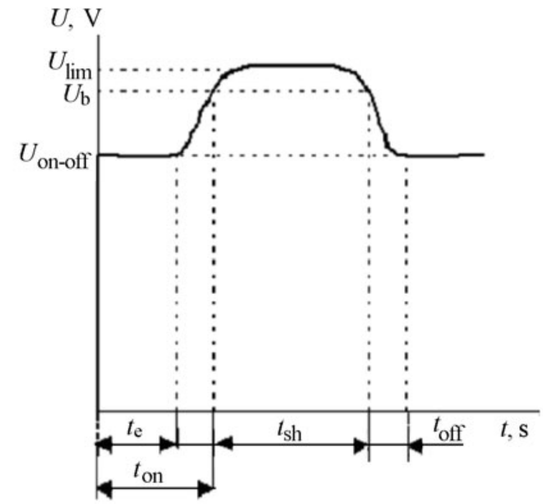


Fig. 4. Time dependence of the temperature difference and external generator current in applying a standard pulse to the limiter diode: 1) dependence of I on t; 2) dependence of T on t; 3) time dependence of the junction temperature before the moment of p–n junction heating.

Fig. 5. Time dependence of voltage in applying a standard current pulse to the limiter diode.

$$T_{\text{p}} - T_{\text{ext}} = \frac{\Delta T_{\max}\tau_{\text{pulse}}}{2q_{\text{on}}} I_{\max} e^{-\frac{2t}{\tau_{\text{pulse}}}}. \tag{17}$$

Figures 4 and 5 diagrammatically represent the time dependences of current I, temperature ΔT, and voltage U when a standard pulse is applied to the diode. The plots ignore the scale correspondence but show all important features of the process influencing the shape of these curves.

As shown in Fig. 4, in the regime of turning on the diode, the rate of decrease in the temperature of the p–n junction is higher (curve 2) than the rate of decrease in the current (curve 1); therefore, the p–n junction acts as a temperature potential generator with the following characteristics:

a) $t_0 - t_{\text{on}}$ section (leading edge of the applied current pulse): the temperature increases depending on the time by the linear law and at the time t_{on} it reaches the maximum value of $T_{n\text{–}p^+}$;

b) $t_{\text{on}} - t_{\text{off}}$ section: the temperature does not vary $(T_{n\text{–}p^+} - T_{\text{ext}})$ = const;

c) the t_{off} section can be neglected since it is rather small and has no significant effect on the shape of the $\Delta T = f(t)$ curve;

d) in the section from t_{off} to t_{pulse}, the temperature potential is determined by relation (17).

Relation (17) permits determining the temperature difference between the diode and the environment at any moment of the external pulse acting on the limiter diode, as well as the maximum temperature in the crystal.

Under the action of the pulse voltage the junction temperature will increase and the thermal process will be determined by the dissipated power. In this case, as the initial temperature T_0, the temperature of the diode without account for the reverse voltage U_{rev} acting on it and the voltage corresponding to the maximum current $(U_{\text{rev}} \le U_{\max})$ is assumed. The initial temperature T_0 will be higher than the ambient temperature T_{ext} since, due to the leakage current I_{leak} on the diode, the power dissipates:

$$P_{\text{leak}} = I_{\text{leak}} U_{\max}, \tag{18}$$

which can make a certain correction to the determination of the temperature difference between the diode and the environment.

Dynamic regime. The thermal flow in the dynamic regime is defined by the relation for the thermal energy

$$Q = I^2(t)\,Rt\,. \tag{19}$$

In the linear section (leading edge of the test pulse, see Fig. 3),

$$I(t) = \beta t = I_{\max}\frac{t}{t_{\text{on}}}\,. \tag{20}$$

Substituting the expression for the current (20) into the expression for the thermal energy (21), we obtain

$$Q = \frac{I^2(t)\,Rt_{\text{on}}}{2} = \frac{I_{\max}^2 Rt^2}{2t_{\text{off}}}\,. \tag{21}$$

Then the thermal flow Φ_1 will be determined by the expression

$$\Phi_1 = \frac{dQ}{dt} = \frac{I_{\max}^2 Rt}{t_{\text{on}}}\,. \tag{22}$$

As is seen from expression (22), with R being invariable, the thermal flow depends linearly on the time and reaches the maximum value at $t = t_{\text{on}}$:

$$\Phi_{\max} = I_{\max}^2 R = P\,. \tag{23}$$

In the exponential section of the standard pulse (see Fig. 3), the current decreases according to the formulas

$$I = I_{\max} e^{-\frac{t}{\tau_{\text{pulse}}}}\,, \tag{24}$$

$$Q = RtI_{\max}^2 e^{-\frac{2t}{\tau_{\text{pulse}}}}\,, \tag{25}$$

$$\Phi_2 = \frac{dQ}{dt} = RI_{\max}^2 e^{-\frac{2t}{\tau_{\text{pulse}}}} - \frac{2t}{\tau_{\text{pulse}}} RI_{\max}^2 e^{-\frac{2t}{\tau_{\text{pulse}}}} = RI_{\max}^2 e^{-\frac{2t}{\tau_{\text{pulse}}}}\left(1 - \frac{2t}{\tau_{\text{pulse}}}\right). \tag{26}$$

The correction between brackets associated with the ratio t/τ_{pulse}, as is seen from expression (26), is effective only at $t > \tau_{\text{pulse}}$. Neglecting this correction, we have

$$\Phi_2 = RI_{\max}^2 e^{-\frac{2t}{\tau_{\text{pulse}}}} = Pe^{-\frac{2t}{\tau_{\text{pulse}}}}\,. \tag{27}$$

At the same time the thermal process should proceed with a thermal constant

$$\tau = R_{\text{t}}^1 C_{\text{t}}\,,$$

where $R_{\text{t}}^1 = \dfrac{Rq_{\text{on}}}{2C_{\text{t}}U}$, then

$$\Phi_2 = Pe^{-\frac{2t}{\tau}}\,. \tag{28}$$

Comparing expressions (27) and (28), we can draw the following conclusions:

1) if the time constant of the growing part of the arriving pulse is equal to $\tau_{\text{pulse}} < R_{\text{t}}C_{\text{t}}$, then the temperature of the depletion region of the p–n junction does not exceed T_{n-p^+};

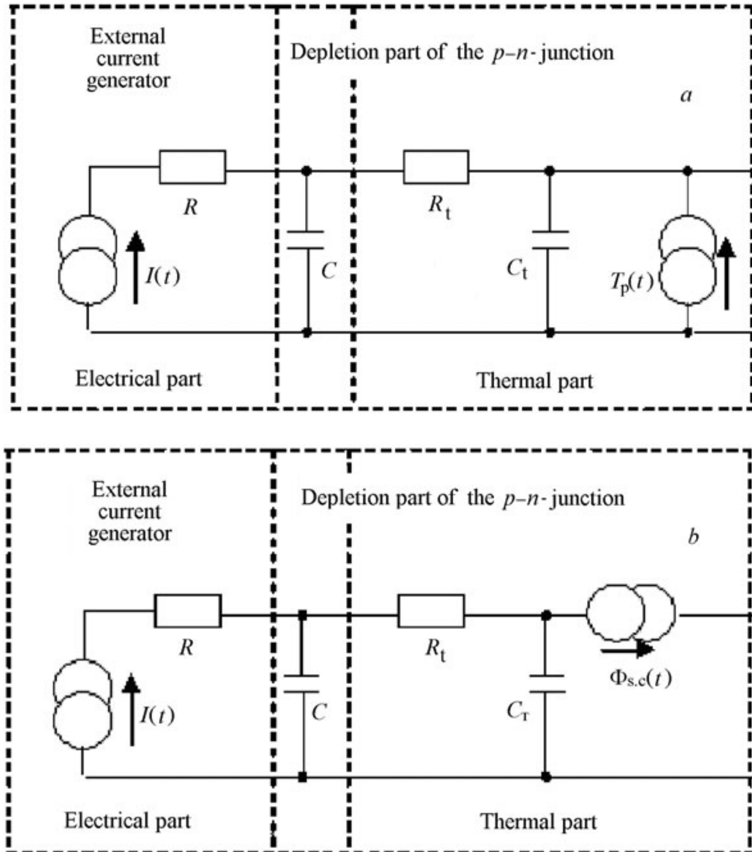


Fig. 6. Equivalent circuits of the temperature potential generator (a) and the thermal flow generator (b).

2) at a time constant $\tau_{pulse} = R_t C_t$, when the temperature potential is equal to the temperature of the space charge layer $T_p = T_{n-p^+}$ and does not vary with time, the diode is in thermal equilibrium: the input electric power is equal to the removed thermal power; this is the most optimal variant of the limiter diode design;

3) at a time constant $\tau_{pulse} > R_t C_t$, when the temperature potential is higher than the temperature of the space charge layer $T_p > T_{n-p^+}$, the diode is superheated.

It should be noted that the time after the turn-on and after the turn-off leads to additional delays in the thermal process. These delays can manifest themselves when fairly high-power and short pulses comparable in time are intercepted (for high-power limiter diodes $t_{on} \sim$ 3–5 ns depends on the external generator, and $t_{off} \sim$ 50 ns). These delays are incomparably shorter than the duration of the front and the decrease in the test pulse and can be ignored in the process of testing.

Thus, the depletion region of the p–n junction of the limiter diode under the action of the test pulse is considered as a generator of a thermal flow passing through its boundaries:

at the pulse front $(0 - t_{on})$:

$$\Phi_1 = \frac{I_{max}^2 R t}{t_{on}}, \tag{29}$$

at t = t_{on} it reaches the maximum value of $\Phi_{max} = I_0^2 R_{ohm} = P$ equal to the input power;

in the exponential section of the acting pulse:

$$\Phi_2 = R I_{max}^2 e^{\frac{2t}{t_{pulse}}} = \Phi_{max} e^{-\frac{2t}{R_t^1 C_t}} = P e^{-\frac{2t}{\tau_{pulse}}}. \tag{30}$$

The equivalent circuit of the limiter diode consists of an external current generator with a resistor connected in series and a parallel capacitor depending on the time, the thermal resistance, and the capacity of the space-charge region. In the case where it is necessary to determine the maximum temperature of the limiter diode, it is expedient to use a temperature potential generator (Fig. 6a). To calculate the temperature distribution in the diode, a thermal flow generator can be used (Fig. 6b). In the given models, the temperature as a function of the time and the coordinate obeys the same laws as the voltage in the equivalent electric circuit.

Conclusions. On the basis of the calculation of the heat transfer and heating of the *p–n* junction in the regime of turning on and applying pulse voltage to the diode, we have obtained its thermal models in the form of a temperature potential generator and a thermal flow generator that make it possible to relate the heat transfer processes to the ultimate permissible operating conditions of silicon voltage limiters.

NOTATION

C_t, heat capacity of the depletion region of the *p–n* junction, $J \cdot K^{-1}$; C, barrier capacitance of the *p–n* junction, Φ; c, specific capacity of the semiconductor, $J \cdot g^{-1} \cdot K^{-1}$; e, electron charge; E, electric field intensity in the depletion region of the junction, $V \cdot cm^{-2}$; E_{max}, maximum electric field in the depletion region of the junction, $V \cdot cm^{-2}$; I, external generator current, A; I_{max}, maximum current amplitude, A; I_{leak}, surface leakage currents, A; j, current density flowing through the *p–n* junction, $A \cdot cm^{-2}$; N, impurity concentration in the weakly doped region, cm^{-3}; n, weakly doped layer of the electron semiconductor; n^+, highly doped layer of the electron semiconductor; P, electric power, $W \cdot cm^{-3}$; P_{leak}, p^+, power dissipated by the diode due to the current leakage, W; p_f, electric power density, Whighly good layer of the hole semiconductor; Q, quantity of thermal energy, J; Q_{n-p^+}, thermal energy released in the depletion region of the *p–n* junction, J; q, charge of mobile carriers, C; q_{on}, quantity of the total charge arising in the depletion region of the diode after the turn-on, C; R, internal resistance of the external generator, Ω; R_t, effective thermal resistance, $K \cdot J^{-1} \cdot s$; R_t^1, effective thermal resistance at $U_g = U$, $K \cdot J^{-1} \cdot s$; R_{ohm}, ohmic resistance of the diode; S, area of the *p–n* junction, cm^2; T_{ext}, ambient temperature, K; T_p, temperature potential, K; T_{n-p^+}, temperature of the depletion region of the *p–n* junction, K; ΔT, temperature difference between the diode and the environment, K; ΔT_{max}, maximum temperature difference between the diode and the environment, K; $T_{s.c}$, temperature of the space charge region, K; T_{on-off}, junction temperature in the regimes of turning on and off, K; t, time, s; t_0, time denoting the beginning of the arriving pulse, s; t_c, time needed for charging the barrier capacitance of the junction, s; t_e, energy relaxation time, s; t_{on}, turn-on time of the limiter diode, s; t_{off}, turn-off time of the limiter diode, s; $t_{p.c}$, peak current gaining time, s; t_{pulse}, arriving pulse duration, s; t_{sh}, shock wave propagation time, s; U, voltage, V; U_b, breakdown voltage, V; U_{max}, maximum voltage of the *p–n* junction at $I = I_{max}$, V; U_g, generator voltage, V; U_{rev}, reverse bias voltage of the diode, V; v_s, saturation velocity of charge carriers, $cm \cdot s^{-1}$; v_{sh}, shock wave velocity, $cm \cdot s^{-1}$; V, volume of the depletion region, cm^3; W, width of the depletion region of the *p–n* junction, cm; X_0, coordinate of the origin in which $E = E_{max}$, cm; x, coordinate along the *p–n* junction, cm; β, rate of current rise near the standard pulse edge, $A \cdot s^{-1}$; γ, coefficient determined by the ratio U_{max}/U; ε, permittivity of the semiconductor; ε_v, electrical permittivity of vacuum, $\Phi \cdot cm^{-1}$; ρ, density of the semiconductor material, $g \cdot cm^{-3}$; τ_{pulse}, thermal time constant of the arriving pulse, s; τ_{max}, maximum value of the time constant of the thermal process, s; τ, thermal time constant, s; Φ_1, thermal flow in the linear section of the current pulse, $J \cdot s^{-1}$; Φ_2, thermal flow in the exponential section of the current pulse, $J \cdot s^{-1}$; Φ_{max}, maximum value of the thermal flow, $J \cdot s^{-1}$; $\Phi_{s.c}$, thermal flow in the space charge region, $J \cdot s^{-1}$. Subscripts: on, turn-on; off, turn-off; g, generator; pulse, pulse; leak, leakage; 0, initial value; v, vacuum; max, maximum; s, saturation; c, charge; e, energy; $n-p^+$, $n-p^+$ junction; ext, external; t, thermal; lim, limiter; ohm, ohmic; p, potential; p.c, peak current; s.c, space charge; rev, reverse.

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