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DEGRADATIONS OF SEMICONDUCTOR DEVICES UNDER PULSED HEAT OVERLOADING

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The linear heat model of degradations of semiconductor devices under pulsed electric overloading has been constructed. Expressions for temporal dependencies of the temperature under different forms of pulse of current are obtained.

The thermal degradations are one of the general reasons of refusal of radioelectronic equipment (REE) under pulsed electrical overload. The special danger present heat overloading of semiconductor devices, which forms the element base of REE. For determination of critical levels of energy, that lead to arising the thermal damage, use linear heat model, adjusting the dependency an threshold power of thermal damage on duration of square-wave form pulse thermal overloading in the manner of

$$P_{ï}/S = B_1\,(T_{ï} - T_{í})\,t^{-0,5}\,, \qquad (1)$$

where S - p-n junction area, $B_1 = \sqrt{\pi k_T \rho C_p}$ - constant, defined by thermal parameters of material, $T_í$, $T_ê$ - initial and final temperature of material accordingly [1]. As a degradation effect it is possible to understand any phenomena, adjusting to change the semiconductor device characteristics at achievement of the temperature of junction $T_ê$. So, if as final temperature the melting temperature of semiconductor is considered, then degradation effect reveals itself in the manner of junction penetration and irreversible damage of semiconductor device. The value $w_B = B_1(T_{ê} - T_{í})$ (W-B constant) characterizes the susceptibility of semiconductor device of different types to thermal overloading.

To determine the temporal dependencies of semiconductor temperature under arbitrary pulse form of electric overloading it is possible to get following expression by means of Dhuamel integral [2]

$$T(t) = T_í + \frac{1}{C_p \rho}\int_0^t P(\tau)\frac{d}{d(t-\tau)}\left[H(r, t-\tau)\right]d\tau\,, \qquad (2)$$

where $H(r,t)$ - transient response, representing the reaction on electric overloading in form of unit-step Heaviside function; U_j and R_b - parameters of equivalent scheme of semiconductor sample (fig.1.); $P(t)$ - instantaneous power of electric overloading under current flow $i(t)$:

$$P(t) = i(t)U_j + i^2(t)R_b\,. \qquad (3)$$

Using (2), will get for overloading in the form of square-wave pulse by height P_0

$$T(t) = T_í + P_0\left[H(r,t) - H(r, t-\tau)\right], \qquad (4)$$

or for normalized temperature with account (1)

$$f(t) = \frac{T(t) - T_í}{T_ê - Ò_í} = \int_0^t P(\tau)\frac{d}{d(t-\tau)}\left[\frac{1}{P_0(t-\tau)}\right]d\tau =$$

$$= \frac{1}{2Sw_B}\int_0^t P(\tau)\frac{1}{\sqrt{t-\tau}}\,d\tau\,. \qquad (5)$$

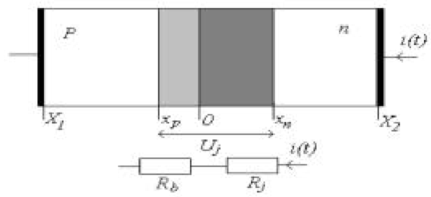

Fig.1. The equivalent scheme of semiconductor sample. $\lfloor x_p, x_n \rfloor$ *- depletion region;* $\lfloor X_1, x_p \rfloor$ *and* $[x_n, X_2]$ *- quasi-neutral regions of semiconductor;* R_b *and* R_j *- accordingly resistance of quasi-neutral and depletion regions;* U_j *- p-n junction voltage.*

The expression (5) allows enough simply to derive formulas for temporal dependencies of semiconductor sample temperature sample under arbitrary forms of pulse of current with duration $\tau_è$ [3]:

1. The square-wave pulse:

$$f(t) = \frac{1}{2Sw_B}\left(I_0 U_j + I_0^2 R_b\right)\sqrt{t}\,.$$

2. The triangular pulse:

$$f(t) = \frac{4}{3}\frac{I_m U_j}{w_B S \tau_u}\left[t^{3/2} - t_1^{3/2} - \left(\frac{\tau_u}{2}\right)^{3/2} + \right.$$

$$\left. + \frac{8 I_m R_b}{5 U_j \tau_u}\left(t^{5/2} - \frac{13}{2}t_1^{5/2}\right)\right],$$

where $t_1 = t - \tau_u/2$

3. Exponential pulse:

$$f(t) = \frac{I_0 U_j \sqrt{\tau}\; D\left(\sqrt{t/\tau}\right) + I_0^2 R_b \sqrt{\tau/2}\, D\left(\sqrt{2t/\tau}\right)}{S w_B}\,,$$

where $D(x) = e^{-x^2}\int_0^x e^{v^2}dv$ - Douson integral [2].

4. Sine-wave pulse:

$$f(t)\frac{I_m U_j\sqrt{\tau_u}}{Sw_B}\{\sin(\pi\theta)C(\pi\theta)-\cos(\pi\theta)S(\pi\theta)+$$

$$\left.+\frac{I_m R_b}{\sqrt{2}U_j}[\theta-\cos(\pi\theta)C(\pi\theta)-\sin(\pi\theta)S(\pi\theta)]\right\},$$

where $\theta=\sqrt{t/\tau_u}$,

$S(x)=\frac{1}{\sqrt{2\pi}}\int_0^x\frac{\sin t}{\sqrt{t}}dt$, $C(x)=\frac{1}{\sqrt{2\pi}}\int_0^x\frac{\cos t}{\sqrt{t}}dt$ - Fresnel integrals.

The graphs of temporal dependencies of normalized temperature for pulses of different form shown on fig.2.

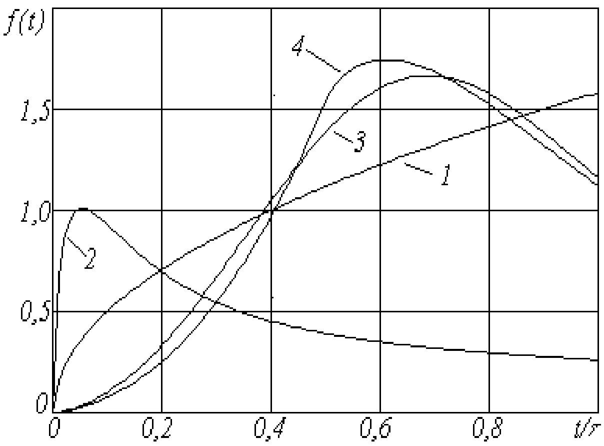

Fig.2. The dependencies of the temperature for different pulse forms: square-wave - 1, exponential - 2, sine-wave - 3, and triangular - 4

For estimation of temporary features of heat process in semiconductor value $\tau_T=\frac{C_P\rho}{k_T}L^2$, named thermal relaxation time constant, is introduced. Here L - typical size of energy-deposition region. Constant τ_T is connected with constant W-B by expression

$$w_B=\frac{k_T}{L}(T_{\hat{e}}-T_{\acute{i}})\sqrt{\pi\tau_T} \quad . \qquad (6)$$

In linear model principle super-positions is kept, i.e. each following pulse deliver an additional heating of the element, and final temperature forms from separate portions of energy, delivered by separate pulses. The dependency of power, which required for realization heat damage under action of pulse sequence, possible gets by means of (2):

$$P_{\ddot{\imath}}=\frac{w_B S}{(T_{\hat{e}}-T_{\acute{i}})\sum_{i=1}^{N}\left[H(r,(i-1)\theta+\tau_u)-H(r,(i-1)\theta)\right]},(7)$$

where θ - pulse time cycle, N - number of pulses in the sequence.

As it can be seen from (7), if the pause between pulses has enough duration, so process a thermal conductivity establishes uniform heat distribution in material, and power of single pulse realize insignificant heating, then the stationary process is fixed in medium, and heat degradations do not appear. But if each following pulse provides the increase of background temperature, that, eventually, as a result of actions of series N of pulses a melting temperature of material is attained. Temporary diagrams of heating process due to sequence of square-wave pulses of power are shown in fig.3. Each pulse with height P_0 can be presented as the difference of Heaviside functions, acting at moments of time $n\theta$ and $n(\theta+\tau_u)$, where θ - pulse time cycle,. $n=0,1,2...$ "Negative power" corresponds to the semiconductor cooling down process during the pause between pulses in consequence of thermal conductivity process.

If the temperature at moment of completion of pulse reaches value of f_1, then to starting of following pulse remaining temperature corresponds to value $f(\theta)$. Herewith for achievement of the temperature of melting f_n = 1 as a result of actions N pulses, it is necessary to satisfy the condition $N\Delta f=1$, where Δf - increase of the temperature during one cycle. When the temperature of heating corresponds to value f_2,, and in pause between pulses occurs cooling down process to starting temperature, as a result the stationary process established.

The expression (1) is got for adiabatic heating regime of semiconductor under the action of short-pulse overload. In linear model is expected that current flows through section less, than real size of junction section [1]. The threshold current value, which is sufficient for heat overloading, may be calculated using estimation of time $t_{\ddot{\imath}}$ that required for realization thermal overload, which are got from (5)

$$\frac{1}{2Sw_B}\int_0^{t_{\ddot{\imath}}}P(\tau)\frac{1}{\sqrt{t_{\ddot{\imath}}-\tau}}d\tau=1; \qquad \frac{df(t_n)}{dt}=0. \quad (8)$$

From these expressions, using also (3), possible get values of maximum current or average power of pulse, under which occur the thermal degradation.

The examples of typical dependencies threshold current of overloading on time of achievement maximal temperature shown on fig.4 for exponential and triangular pulses. The numerical calculation shows that for exponential current the damage approach in narrow range of pulse duration $0{,}653<\sqrt{2t_n/\tau_{\grave{e}}}<0{,}924$; for triangular current thermal degradation occur on trailing edge of pulse $\sqrt{2t_n/\tau_u}>1{,}184$.

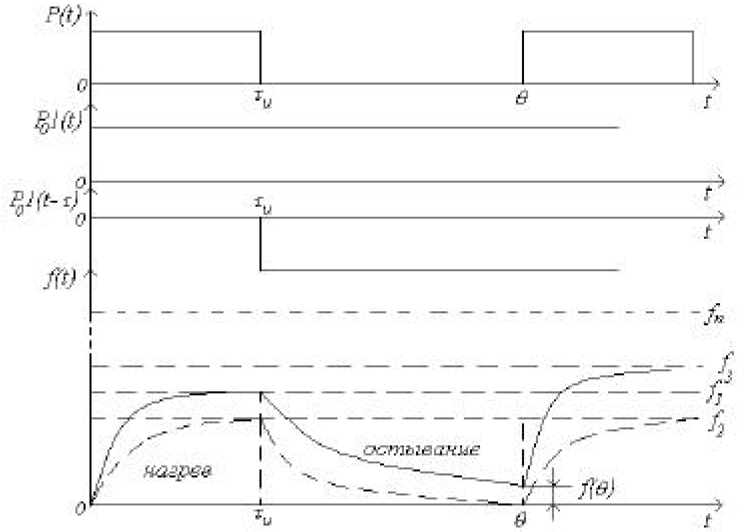

Fig.3. The temporary diagrams of semiconductor heating by sequence of pulses.

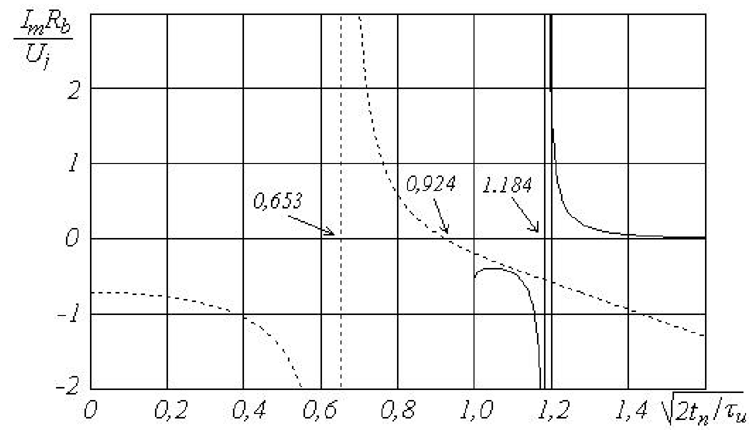

Fig.4. Dependency of threshold current of thermal damage on time of heating toe maximum temperature (the triangular pulse of current - line; the exponential current - dot [2]).

The localization of current results the effect of heat localization, that forms the base of nonlinear model of thermal breakdown of semiconductor [4,5]. In this case nonlinear equation of thermal conductivity results to sharpening regime, for which are executed the condition $f(t) \to \infty$, under $t \to t_0$, i.e. during finite time gap possible achievement of infinite temperature in local areas of medium. In [4] is shown that one of the general reasons of arising the sharpening regime is uniformly distribution of starting temperature of sample, increasing in consequence of semiconductor conductivity rising advance of its thermal conductivity under current flowing and Joules heating of semiconductor. Besides, in extrinsic semiconductor possible determination of nonuniform bulk resistance, that results the effect of current filament already on initial stage of shaping thermal structure [6,7].

As a result of analysis of processes semiconductor elements heating the temporary dependencies of the temperature of sample under pulsed current loading are got. It allows to define the critical regimes of operation REE and take into account them under defining of reasons of refusals and studies of questions to electromagnetic compatibility.

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