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The method of determining the Probability of Affection of the Semiconductor Elements under the influence of the Multifrequency Space-Time Signals

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ABSTRACT

The studies to improve the affection accumulation method for the case of influence to the semiconductor element base by the multi-frequency space-time signals have been conducted. The estimates of the probability of affection of the semiconductor element under the influence of the multifrequency space-time signals have been obtained.

As a result of the researches conducted, the method of affection accumulation for the case of the influence of MF STS on the semiconductor element base has been improved. This method involves the usage of statistical characteristics of thermal energy to estimate the probability of degradation of the p-n junctions for normal (diodes, transistors) and equable (integrated circuits) distribution laws.

Key words: semiconductor, affection, probability, microprocessor technology, control system, space-time signal, mathematical model.

1. INTRODUCTION

The use of new physical principles and technical solutions when creating perspective generating means, the improvement of theoretical methods of affection of the semiconductor elements necessitate the explanation of the effects of irreversible affection when using a sequence of short signals.

The purpose of the work is to develop a method of affection accumulation, which implies that under the influence of a single impulse there is a slight local change in the structure, for example, the formation of a defect. The failure of a device will occur when a certain critical number of defects is reached.

Based on the Arrhenius activation theory, it is advisable to conduct a number of calculations of the affection of the semiconductor elements and obtain the probabilistic affection estimates using the normal and equable distribution laws for the thermal theory that excites the p-n junction, including also taking into account the number of impulses, duty cycle and the power of the generated signal.

2. MAIN MATERIAL

The analysis of a large number of experiments [1, 2, 3 4] shows that the exposure mode (mono impulse or pack) plays a significant role in assessing the affection levels of the semiconductor elements. In this case, the affection is, as a rule, probabilistic in nature. The experiments also show that the affection of semiconductor elements in a single impulse mode will occur when the energy (power) of the impulse is significantly greater than the power and energy of one impulse when using a sequence of signals of nanosecond duration. At a high repetition rate, this effect is usually explained by the accumulation of heat from impulse to impulse.

It is necessary that the period of the sequence be commensurate with the relaxation time of the rectifying contact of the semiconductor element. However, as the experiment shows, the degradation effect is also observed in the case when the pack period is much longer than the thermal constants, for example, at frequencies of tens and hundreds of Hz.

A qualitative explanation of degradation effects when using a sequence of short signals at a high duty cycle can be given using the affection accumulation model [1, 11, 13, 15]. In this model, it is assumed that under the influence of a single impulse, a slight local change in the structure occurs, for example, the formation of a defect. The failure of a device will occur when a certain critical number of defects is reached.

The existing theories of statistical failures of the semiconductor elements have been developed for cases of rather slow degradation processes such as diffusion or electro migration [1, 12, 14].

Let us suppose that under the influence of a sufficiently high-intensity radio impulse, the defects in the structure of the rectifying contact of a semiconductor element, for example, a diode, occur, which leads to changing its characteristics. Such a characteristic may be the differential conductivity p(t) of the rectifying contact. Under the action of one sequence signal, the parameter p(t) changes by a certain amount δp. A change in the characteristic of the transmitting radio line will be associated with a deviation of p(t) value from the nominal p_0 value, which characterizes the normal mode of operation.

When a certain critical value $p(t) = p_{cr}$ is reached, the semiconductor elements will be affected. It is obvious that the sizes of the defect depend on the impulse energy, and their number is determined by the structure of the semiconductor, its homogeneity. The number of impulses causing the affection of the semiconductor element may vary from sample to sample. The observed decrease in the power of the impulses causing the affection of a diode with an increase in the repetition frequency is preconditioned by the fact that the affection of the semiconductor element can occur by creating a large number of defects. The energy of formation of each of them is comparatively small. To affect an element with a single impulse, the creation of one large defect is required, while considerable energy is required to create it.

A change in the parameter δp under the action of one powerful STS (space-time signal) of τ_{STS} duration will be proportional to the velocity of the affection process V [1, 7]:

$$\delta p=\int_0^{\infty} V(t)dt . \qquad (1)$$

The process of increasing degradation to the complete failure of the element will occur as a result of the influence of the MF (multi frequency) STS sequence. To estimate the rate of change of the p parameter, it is advisable to use the Arrhenius activation theory, according to which [1, 2, 6, 8]:

$$V(t)=V_0\exp\left(-\frac{E_a}{k_B T}\right), \qquad (2)$$

where E_a is the MF STS sequence energy;

V_0 – a constant depending on the defect type;

K_B – the Boltzmann constant;

T – the rectifier contact temperature, which changes under the action of the MF STS sequence.

If the change in the p parameter occurs under the action of several impulses, then the activation energy and the constant V_0 can be different for different impulses. We assume that the changes in these parameters from impulse to impulse are small, and these changes can be neglected. In this case, using (1) we can obtain an equation describing the change in the p(t) parameter:

$$\frac{dp(t)}{dt}+\gamma p(t)=V_0\exp\left(-\frac{E_a}{k_B T(t)}\right), \qquad (3)$$

where $\gamma p(t)$ is the relaxation parameter describing the process of restoration of a semiconductor structure.

The solution of the equation (3) has the following form:

$$p(t)=V_0\exp(-\gamma t)\int_0^{t}\exp\left(-\frac{E_a}{k_B T(t')}\right)dt' . \qquad (4)$$

To obtain the quantitative estimates of the differential conductivity of the rectifying contact when influenced by an MF STS pack, we consider a heat release mode with an impulse duration of τ_{STS} and a period of the T_{STS} sequence such that the transition temperature has time to recover to the initial value between the effect of the impulses.

MF STS parameters: the signal duration at a level of 0,5 is of the order value of $\tau_i = 5$ ns, the steepness of the leading edge is 1,5 ns, the level of the first side lobe is about 10dB. It is possible to approximate a single STS formed by a rectangular impulse with an accuracy sufficient for subsequent calculations. The calculation error in this case will be no more than 15%.

The change in the p(t) parameter under the action of a pack on N impulses takes the form [1, 3, 5]:

$$p_N=V_0\eta(N,T_{STS},\gamma)\exp(-\gamma T_{STS})\int_0^{T_{sts}}\exp\left(-\frac{E_a}{k_B T(t)}+\gamma t\right)dt . \qquad (5)$$

where $\eta(N,T_{STS},\gamma)=\frac{1-\exp(-\gamma N T_{STS})}{\exp(-\gamma T_{STS})}\exp(-\gamma T_{STS}+\gamma\tau_{STS})$.

In the case under consideration, the local affection and formation of structural defects in the p-n junction are preconditioned by its intense local heating under the action of impulses. The effective local temperature T(t) in (5) can be determined from the solution of the thermal conductivity equation [2, 4]:

$$T(t)\approx T_0+\frac{2P}{C\rho S}\sqrt{\frac{t}{\pi K}} \qquad (6)$$

$$\tau_{rel} < t < \tau_{STS},$$

$$T(t) \approx T_0 + \left[T(\tau_{STS}) - T_0\right] \operatorname{erf}\left(\frac{d + 2\sqrt{K\tau}}{2\sqrt{K\tau}}\right) \qquad (7)$$

$$t > \tau_{STS},$$

where P is the power dissipated in the p-n junction;

T_0 – the initial temperature;

C, ρ – the thermal capacity and the conductor density;

$\tau_{rel} = d^2/K$ – the relaxation time;

K – the conductor thermal diffusivity;

S, d – the area and width of the p-n junction.

By substituting (6), (7) into (5), for the condition $E_a > KT$ we obtain the estimate [1] for p_N:

$$p_N = V_0 \tau_{STS} \exp\left[-\frac{E_a}{k_Б T(\tau_{STS})}\right] \eta\left(N, T_{STS,\gamma}\right), \qquad (8)$$

where $\eta(N, T_{STS}, \gamma) = \dfrac{1-\exp(-\gamma N T_{STS})}{\exp(-\gamma T_{STS})} \exp(-\gamma T_{STS} + \gamma \tau_{STS})$.

It is obvious that the statistical fluctuations of the differential conductivity of the rectifying contact p(t) are associated with a random energy value E_a, and it is exactly its fluctuations that determine the damage statistics (as the defects formed under the action of a series of overload impulses can occur at different centers, furthermore, the conditions of formation of defects can change).

The probability of affection of a semiconductor element can be estimated as the probability that the p parameter exceeds the critical value p_{cr}:

$$P = \int_{p_{cr}}^{\infty} g(p)\, dp,$$

where g(p) is the density of the probability of a random p value.

If the distribution density of probability $f(E_a)$ is known for a random continuous value E_a, then the probability of affection of the semiconductor element P can be estimated as the probability that the p parameter exceeds the critical value p_{cr} [1]:

$$P = \int_{E_0}^{E(T, T_{STS}, \gamma, \eta, \delta)} f(E_a)\, dE_a, \qquad (9)$$

where $E(T, T_{STS}, \gamma, \eta, \delta) = k_B T\left\{\ln(\delta) + \ln\left[\eta\left(N, T_{STS}, \gamma\right)\right]\right\}$ – the solution of the equation (8) at $p_N = p_{cr}$; $\delta = V_0 \tau_{STS}/p_{cr}$.

To estimate the probability of affection of a semiconductor element, we will assume that the energy E_a has a normal distribution law with an average E_{av} and a Δ^2 dispersion.

Such a law can be justified for simple structures, for example, diodes or transistors.

Then the probability of affection (exceeding of p_{cr}) for $E_{av} > E_0$ will be [1]:

$$E(T, T_{STS}, Q, \eta, \delta) \geq E_{av}$$

$$P = \Omega \times \Delta\sqrt{\frac{\pi}{2}} \times \left\{\operatorname{erf}\left(\frac{Eav - E_0}{\sqrt{2}\Delta}\right) + \operatorname{erf}\left(\frac{E(T, T_{STS}, Q, \eta, \delta) - E_{av}}{\sqrt{2}\Delta}\right)\right\}, \qquad (10)$$

$$E_0 < E(T, T_{STS}, Q, \eta, \delta) < E_{av}$$

$$P = \Omega \times \Delta\sqrt{\frac{\pi}{2}} \times \left\{\operatorname{erf}\left(\frac{E_{av} - E_0}{\sqrt{2}\Delta}\right) - \operatorname{erf}\left(\frac{E_{av} - E(T, T_{STS}, Q, \eta, \delta)}{\sqrt{2}\Delta}\right)\right\},$$

where $\Omega = \Delta\sqrt{\dfrac{\pi}{2}}\left\{1 + \operatorname{erf}\left(\dfrac{E_{av}}{\sqrt{2}\Delta}\right)\right\}$;

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp\left(-u^2\right) dua.$$

If the energy of the MF STS E_a sequence has an equable distribution (which is typical for integrated circuits) in the $E_0 \leq E_a \leq E_0 + \Delta E$ range, then the probability of affection will be:

$$\begin{cases} P = 0 & k_B T\left[\delta + \ln(\eta)\right] \leq E_0, \\ P = \dfrac{k_B T\left[\delta + \ln(\eta)\right] - E_0}{\Delta E} & E_0 \leq k_B T\left[\delta + \ln(\eta)\right] \leq E_0 + \Delta E, \\ P = 1 & k_B T\left[\delta + \ln(\eta)\right] > E_0 + \Delta E. \end{cases} \qquad (11)$$

Expressions (10), (11) are the main calculated ones and make it possible to obtain the numerical estimates of the probability of affecting P from the number of impulses N, from the period of the impulses of the T_{STS} sequence, from the power P of one impulse.

3. CONCLUSION

As a result of the researches conducted, the method of affection accumulation for the case of the influence of MF STS on the semiconductor element base has been improved. This method involves the usage of statistical characteristics of thermal energy to estimate the probability of degradation of the p-n junctions for normal (diodes, transistors) and equable (integrated circuits) distribution laws.

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