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Short Note

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Predicted Useful Lifetime of Aerospace Electronics Experiencing Ionizing Radiation: Application of BAZ Model

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Abstract

The objective of the analysis is to demonstrate how the Boltzmann-Arrhenius-Zhurkov (BAZ) model, originally suggested by Zhurkov in the kinetic concept of the strength of solids as a generalization of the Arrhenius theory of chemical reactions, can be effectively employed for the prediction of the lifetime of electronic materials experiencing ionizing radiation. The "loading term" $\gamma\sigma$ in the original BAZ model, where σ is the tensile mechanical stress and γ is the sensitivity factor, is replaced with the term $\gamma_R D$, where D is the radiation level and γ_R is the sensitivity factor. Leakage current measured during the failure-oriented-accelerated-testing (FOAT) is considered in our analysis as a suitable indication/criterion of the level of the induced damage. FOAT terminates, when the agreed upon critical value of the leakage current is reached.

The space environment poses an increased risk of failure for electronic and photonic devices (see, e.g., [1-5]). This analysis is an attempt to quantify, on the probabilistic basis, the outcome of a FOAT [6] and to predict the never-zero probability of failure of the material or the device of interest in the actual operation conditions. It is suggested that the flexible and physically meaningful BAZ equation [7,8] that was used previously for a number of applications in microelectronics and photonics reliability problems (see, e.g., [9,10]) is used as the model of choice in the probabilistic design for reliability (PDfR) [11] and FOAT efforts. The multi-parametric BAZ model extends the original Zhurkov model for the situations, when the stressor is not tensile mechanical stress, but any other stimulus that contributes to the degradation of the material or the device (such as, e.g., elevated voltage, electrical current, humidity, temperature, vibrations, light output, etc.) and, since the superposition principle does not work in the reliability engineering, - for the situations, when multiple stressors are applied. Another modification of the Zhurkov model is replacement of the time constant τ_0 (see eq. (1) below) with an expression that considers the role of time and the parameter that characterizes in a particular problem the degree of degradation. In the situation in question it is the leakage current [12].

BAZ equation for the mean-time-to-failure (MTTF) can be written for the case, when the external loading is ionizing radiation, as follows:

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma_R D}{kT}\right) \tag{1}$$

In this equation τ_0 is the time constant, U_0, *eV,* is the basic activation energy that characterizes the propensity of the material or the device to the action of the ionizing radiation, T,^{0} *K* is the absolute temperature, $k = 8.61733x10^{-5}$ *eV/K* is Boltzmann's constant, D, Gy = J/kg, is radiation and γ_R is the sensitivity factor for the case of radiation "stressor". If the exponential law of reliability is used, then the following equation for the probability of non-failure in the case of radiation stressor can be obtained:

$$P = \exp(-\lambda t) = \exp\left(-\frac{t}{\tau}\right) = \left[-\frac{t}{\tau_0}\exp\left(\frac{U_0 - \gamma_R D}{kT}\right)\right] \tag{2}$$

In this double exponential probability distribution function it is considered that the failure rate λ is inversely proportional to the MTTF τ The time τ_0 in this equation is an empirical parameter that characterizes the situation at failure, and its physical nature could be selected depending on the magnitude of the monitored quantity used as a suitable indication of FOAT failure. If, e.g., the level I_* of the leakage

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current *I* is accepted as a suitable characteristic of the level of damage, then the time τ_0 could be represented as, say, $\tau_0 = \frac{1}{\gamma_I I_*}$, where γ_I is the sensitivity factor for this current. Then the formula (2) can be written as

$$P = \exp\left[-\gamma_I I_* t \exp\left(-\frac{U_0 - \gamma_R D}{kT}\right)\right] \quad (3)$$

There are three unknowns in this formula: two sensitivity factors, γ_I and γ_R, and the activation energy U_0. These unknowns can be found using FOAT. Let us show how this could be done.

Testing should be conducted in two steps. At the first step testing should be carried out for the same level of radiation, but for two different temperature levels, T_1 and T_2. Then the following two experimental relationships will be obtained:

$$P_{1,2} = \exp\left[-\gamma_I I_* t_{1,2} \exp\left(-\frac{U_0 - \gamma_R D}{kT_{1,2}}\right)\right] \quad (4)$$

Here $P_{1,2}$ are the measured probabilities of non-failure, $t_{1,2}$ are the corresponding times and I_* is the level of the leakage current that is considered as an indication of the radiation related failure. Since the numerator U_0 - $\gamma_R D$ in the relationships (4) is kept the same, the factor γ_I can be found as

$$\gamma_I = \exp\left(\frac{\frac{T_2}{T_1}\ln n_2 - \ln n_1}{\frac{T_2}{T_1} - 1}\right), \quad (5)$$

where

$$n_{1,2} = -\frac{\ln P_{1,2}}{I_* t_{1,2}} \quad (6)$$

After the sensitivity factor γ_I is determined, the second step of FOAT should be conducted at two different radiation levels to determine the sensitivity factor γ_R. The temperatures at these tests do not have to be the same. Considering that the stress-free activation energy U_0 should remain the same, the following formula for the sensitivity factor γ_R can be obtained:

$$\gamma_R = k\frac{T_1 \ln n_1 - T_2 \ln n_2 + (T_2 - T_1)\ln\gamma_I}{D_1 - D_2}, \quad (7)$$

where the notation (6) is used (the actual numbers are those obtained at this, second, step, and are different, of course, of the numbers obtained at the first step of testing). While the temperatures T_1 and T_2 do not have to be the same, the formula (7) could be simplified, if they are kept the same. Then the factor γ_R can be evaluated as

$$\gamma_R = kT\frac{\ln\left(\frac{n_1}{n_2}\right)}{D_1 - D_2} \quad (8)$$

Here *T* is the testing temperature. In such a situation the factor γ_I does not affect the factor γ_R. Finally, after the sensitivity factors γ_I and γ_R are evaluated, the activation energy can be found as

$$U_0 = -kT_1 ln\left(\frac{n_1}{\gamma_1}\right) + \gamma_R D_1 = = kT_2 ln\left(\frac{n_2}{\gamma_1}\right) + \gamma_R D_2 \quad (9)$$

Let, e.g., the following data have been obtained at the first step of FOAT:

1) After t_1 = 35 *h* of testing at the temperature of T_1 = 60 °C = 333° *K* and after the total ionizing dose of *D = 1.0 Gy = 1.0 J/kg* was obtained, 10% of the tested devices reached the critical level of the leakage current of I_* = 3.5 *μA* and, hence, failed, so that the recorded probability of non-failure is P_1 = *0.9*;

2) After t_2 *= 50 h* of testing at the temperature of T_2 *= 85* °C *= 358° K* and at the same radiation level, 25% of the tested samples failed, so that the recorded probability of non-failure is P_2 = 0.75.

Then the formulas (6) yield:

$$n_1 = -\frac{\ln P_1}{I_* t_1} = -\frac{\ln 0.9}{3.5x35} = 8.6009x10^{-4}\mu A^{-1}h^{-1};$$

$$n_2 = -\frac{\ln P_2}{I_* t_2} = -\frac{\ln 0.75}{3.5x50} = 16.4390x10^{-4}\mu A^{-1}h^{-1};$$ and

the formula (5) results in the following value of the parameter γ_I:

$$\gamma_I = \exp\left(\frac{\frac{T_2}{T_1}\ln n_2 - \ln n_1}{\frac{T_2}{T_1} - 1}\right) = = \exp\left(\frac{\frac{358}{333}\ln 16.4x10^{-4} - \ln 8.60x10^{-4}}{\frac{358}{333} - 1}\right) = = 9.1836\mu A^{-1}h^{-1}$$

At the second step of FOAT one can use, without conducting additional testing, the following information from the first step:

1) After t_1 *= 35 h* of testing at the temperature of T_1 = *60* °C *= 333° K* and after the total ionizing dose of *D = 1.0 Gy = 1.0 J/kg* was obtained, 10% of the tested devices reached the critical level of the leakage current of I_* = 3.5 *μA* and, hence, failed, so that the recorded probability of non-failure is P_1 = *0.9*; but, in addition, conduct FOAT for a different radiation level of, say, D_2 *= 2.0 Gy*. Let us assume that the following information has been obtained: but, in addition, FOAT should

be conducted for a different radiation level.

2) After t_2 = *10 h* of testing at the same temperature and after the total radiation dose of D_2 = *2.0 Gy*, 40% of the tested samples failed, so that the probability of non-failure is $P_2 = 0.6$.

Then the second formula in (6) yields:

$$n_2 = -\frac{\ln P_2}{I_* t_2} = -\frac{\ln 0.6}{3.5x10} = 145.9502x10^{-4}\mu A^{-1}h^{-1};$$

and the equation (8) results in the following γ_R value:

$$\gamma_R = kT\frac{\ln\left(\frac{n_1}{n_2}\right)}{D_1 - D_2} =$$

$$= 8.61733x10^{-5}x333\frac{\ln\left(\frac{8.6009x10^{-4}}{145.9502x10^{-4}}\right)}{1-2} =$$

$$= 0.081249eVGy^{-1}$$

After the sensitivity factors of the leakage current and the radiation are found, the activation energy can be determined as

$$U_0 = -KT_1 ln\left(\frac{n_1}{\gamma_1}\right) + \gamma_R D_1 = -8.61733\times10^{-5}\times333 ln\left(\frac{8.6009\times10^{-4}}{9.1836}\right) + 0.081249 =$$

$$= 0.266178 + 0.081249 = 0.3474ev$$

The expected time-to-failure (TTF) can be determined from (3) as follows:

$$t = -\frac{\ln P}{\gamma_I I_*}\exp\left(\frac{U_0 - \gamma_R D}{kT}\right) \quad (10)$$

This time depends, of course, on the expected (specified) probability *P*.

If, e.g., the specified probability of non-failure in actual operation conditions is, say, *P* = 0.999999, the outside temperature is *T = -150* °C = *123° K* and the radiation level is *D = 1.0 Gy*, then, with the obtained FOAT data we find:

$$t = -\frac{\ln 0.999999}{9.1836x3.5}\exp\left(\frac{0.3474 - 0.081249x1.0}{8.61733x10^{-5}x123}\right) =$$

$$= 25010.57h = 2.85 years$$

Future work should focus on experimental verification of the validity of the suggested model, as well as on the consideration of the combined action of several stressors that make physical sense. This could be done by applying the multi-parametric BAZ [9].

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