Reliability Prediction of Electronic Devices, Considering the Gradual Failures

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***Abstract*—**The authors suggest a method of the reliability prediction for electronic devices, considering possible gradual failures. Reliability prediction value of the new samples can be given using the degradation (ageing) parameters' model obtained by preliminary research of a sample of products.

***Keywords*—**Reliability; prediction; electronic devices; physical-statistical models; gradual failures.

I. Introduction

During the operation time of electronic devices (ED) in electronic circuits their functional parameter (denote by y) changes and can be considered as a time-function $t – y(t)$. The gradual change of parameter $y(t)$ and its output outside the established norms defines such concept as a gradual failure. Reliability to gradual failure of ED characterizes ability to save the level of functional parameter $y(t)$ within the norms, specified in the technical documentation or by the customer, for a given time t_G at selected modes and conditions.

This reliability was named "parametric". A quantitative measure of parametric reliability level is the probability $P(t_G)$. It can be defined as [1–3]

$$P(t_G) = P\{a \le y(t) \le b,\ t \le t_G\}, \tag{1}$$

where $P\{\ldots\}$ – probability of execution of the condition specified in the brackets.

Parametric reliability can be considered as a component of the general reliability of ED.

Unexpected failures causes can be largely eliminated as the result of development of electronic devices production technology [1–3]. But it is impossible to eliminate gradual failures that reflect the inherent material properties of ED, in particular aging. This is the reason of rising interest to gradual (wear-out) failures of ED. It is known [1–4] that gradual failures and therefore parametric reliability of ED can be predicted. It is topical to develop a method of obtaining the predicted value of parametric reliability.

II. Physical Modeling of the Parameters' Degradation

To obtain reliable prediction to gradual failures and, therefore, parametric reliability of ED we must have a quantitative model of reliability as a function of degradation function parameter $y(t)$ of time, temperature, electrical load, and other operational factors [1, 2, 5–9]. This model is based on a study of the behavior of ED, not only at the time of failure, but also in gradual change of the functional parameter $y(t)$, that is, the study of the kinetics of failure, and can be obtained from the probabilistic and statistical methods. Degradation model of a functional parameter of ED, constructed in such way, is called physical-statistical [1, 2, 5, 6]. As soon as physical-statistical model of the degradation of the functional parameter $y(t)$ will be obtained, finding the probability defined by (1) is possible from a mathematical point of view. Obtaining physical-statistical model of degradation is facilitated by physical experiment, during the modeling of the most common conditions of failure mechanisms and processes of physical and chemical degradation of the functional parameter $y(t)$. Let us explain some of the mathematical aspects of physical modeling

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of degradation of functional parameters and parametric reliability prediction of electronic devices on these models.

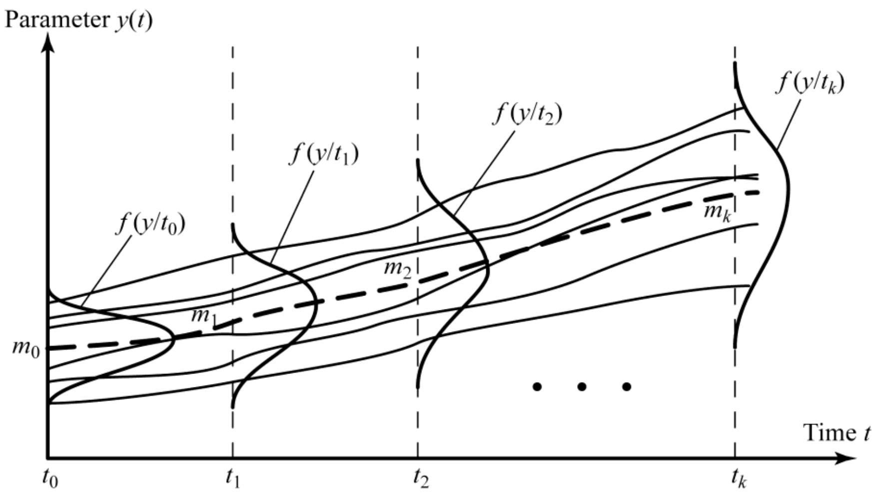
In many cases, the quantitative characteristic of parametric reliability $P(t_G)$ defined by (1) may be obtained on the basis of knowledge of the distribution law of the functional parameter $y(t)$ at the initial time, such as conventional (for the time $t = 0$) density $f(y \mid t = 0)$, and change of function $y(t)$ at time

$$y(t) = \varphi(y_0, t), \quad (2)$$

where φ – symbol of the functional connection; y_0 – value $y(t)$ at time $t = 0$.

The value of probability $P(t_G)$ is the result of changes in the statistical distribution $f(y \mid t = t_G)$ of parameter $y(t)$ during the work time t_G, $t_G = t_1, t_2, \ldots, t_k$ (Fig. 1).

If the function $y(t)$ is monotonic, then parameters' distribution of samples ED is stored in any time points [10–13]. In this case we can talk about saving for a long time not only the form of the distribution, such as the conditional (for time t) distribution density of the functional parameter $f(y \mid t)$, but also a strong correlation of the parameter $y(t)$ for different time points (see Fig. 1). The close correlation is confirmed by experimental studies on high power bipolar transistors (BT) of many types for functional parameters such as collector-emitter saturation voltage ($U_{CE(sat)}$) and static value of the forward current transfer ratio (h_{21E}) [13]. Correlation matrix for the parameter $U_{CE(sat)}$ for high power BT of KT872A type, as an example, is given in Table I. As time points we
considered values of 0, 3 840, 8 320, 12 800, and 17 280 hours.



$t_0, t_1, t_2, \ldots t_k$ – measuring time points;
$m_0, m_1, m_2, \ldots m_k$ – expectation values of parameter y at appropriate time points (dashed line)

Fig. 1 Changing in density of functional parameter $y(t)$ at work ED

TABLE I
The Correlation of Parameter $U_{CE(sat)}$ for KT872A in Time Points

Time Section, h	0	3 840	8 320	12 800	17 280
0	1,0000	–	–	–	–
3 840	0,9588	1,0000	–	–	–
8 320	0,9240	0,9899	1,0000	–	–
12 800	0,9170	0,9868	0,9955	1,0000	–
17 280	0,8931	0,9755	0,9881	0,9969	1,0000

The close correlation between the functional parameters $U_{CE(sat)}$ (or h_{21E}) in different time points can be considered as a basis for prediction the gradual failures, therefore parametric reliability of electronic devices according to statistical data of the parameter at the initial time ($t = 0$). Further parameters $U_{CE(sat)}$ and h_{21E} generally will be regarded as a parameter y.

III. Using of Physical-Statistical Models for Reliability Prediction

Approximate analytic expression of conditional distribution density $f(y \mid t)$ of parameter y for every time $t = t_i$ can be obtained through mathematical transformation of initial distribution $f(y \mid t = 0)$:

$$f(y \mid t = t_i) = \psi[w(y \mid t = 0), t_i], \tag{3}$$

where ψ – symbol of the functional dependence.

Physical-chemical characteristics of the degradation of the functional parameter $y(t)$, obtained by averaging over the studied ED samples, will be included in the form of the coefficients in the right side of equation (3).

Finding the exact analytical expressions for the function $f(y|t = t_i)$ involves considerable mathematical difficulties. So idealization of parameter $y(t)$ and simplifications allowable in determining $f(y|t = t_i)$ justify themselves, because they provide an opportunity to determine, at least approximately quantitative characterization of parametric reliability $P(t_i)$ with the adopted in probability theory rules of finding the value

$$P(t_i) = P\{a \le y(t) \le b, \quad t \le t_i\},$$

using distribution law of random variables [14]:

$$P(t_i) = \int_a^b f\left(y \middle| t = t_i\right) dy = F\left(b \middle| t_i\right) - F\left(a \middle| t_i\right), \tag{4}$$

where $F(a|t_i)$, $F(b|t_i)$ – values of the conditional (for time t_i) distribution function $F(y|t)$ of the functional parameter y, calculated for values $y = a$ and $y = b$.

With streamlined technological process of manufacturing of ED is often observed a normal distribution of the product parameters. We take normal distribution of the functional parameter y as a basis for obtaining the model of degradation. The conditional distribution density y for the given time point t in this case is written as

$$f\left(y \middle| t\right) = \frac{1}{\sqrt{2\pi} \cdot \sigma\left(y \middle| t\right)} \exp\left\{ -\frac{\left[y - m\left(y \middle| t\right)\right]^2}{\left[\sigma\left(y \middle| t\right)\right]^2} \right\}, \tag{5}$$

where $m(y|t)$, $\sigma(y|t)$ – characteristics (parameters) of the normal distribution.

The values $m(y|t)$, $\sigma(y|t)$ represent the average value and standard deviation of the functional parameter y in time point t and in the implicit form include the physical and chemical characteristics of its degradation for interested time t. According to the expression (3) values $m(y|t)$, $\sigma(y|t)$ defined as a function of time t and values $m(y|t = 0)$ and $\sigma(y|t = 0)$, which are the parameters of the normal distribution law at the initial time ($t = 0$):

$$m(y|t) = \varphi_1[t, m(y|t = 0), \sigma(y|t = 0)]; \tag{6}$$

$$\sigma(y|t) = \varphi_2[t, m(y|t = 0), \sigma(y|t = 0)], \tag{7}$$

where φ_1, φ_2 – symbols of functional dependencies that must be determined.

The conditional distribution density (5), obtained from the expressions (6) and (7), can be considered as physical-statistical model of degradation of the functional parameter $y(t)$. To obtain this model prior studies of a samples of interest ED type are need. Such samples will be called the training. Its size n must be at least 60 ... 100 specimens. The construction of the model using training samples, includes a number of steps that can be found in the works [1, 2, 5–9].

The obtained physical-statistical model of the degradation of the functional parameter $y(t)$ in the form of the conditional distribution density (5) can further be used in practice for the multiple parametric reliability prediction of new samples of studied type ED. Prediction is obtained as the probability determined by the expression (1). Predictive value of this probability $P(t)_{pr}$, according to (4) and the hypothesis of normal distribution of the functional parameter y in time sections $t = t_i$, determined by the expression

$$P(t_i)_{pr} = \Phi\left[\frac{b - m(y|t_i)}{\sigma(y|t_i)}\right] - \Phi\left[\frac{a - m(y|t_i)}{\sigma(y|t_i)}\right], \tag{8}$$

where $i = 1, 2, \ldots, k$; $\Phi[\ldots]$ – tabulated normal distribution function [3, 14], found for the argument given in brackets; $m(y|t_i)$ and $\sigma(y|t_i)$ – parameters the normal distribution, calculated from the expressions (6) and (7) for time $t = t_i$.

According to data obtained during the test of operating time (physical modeling) for specimens of the other (control) samples can be found experimental values of the level of parameter reliability $P(t_i)_{ex}$, appropriate to time points t_i. For these goals can be used the expression

$$P(t_i)_{ex} = \frac{r(a \le y \le b)}{r}, \quad i = 1, 2, ..., k, \tag{9}$$

where $r(a \le y \le b)$ – number of specimens of the control sample for which the function parameter $y(t)$ at time t_i is within the norms from a to b; r – the total number of specimens in the control sample (control sample volume).

Possibility of using the building of physical and statistical model for degradation of parameter $y(t)$ for prediction the parameter reliability of new samples of ED for the time points in the range of operating time (t_1 … t_k) can be seen from the average prediction error of parametric reliability. For determining this error there where proposed an expression [1, 2, 13]

$$\Delta_{av} = \sqrt{\frac{1}{k}\sum_{i=1}^{k}\left(\frac{P(t_i)_{pr} - P(t_i)_{ex}}{P(t_i)_{ex}}\right)^2} \cdot 100\%, \tag{10}$$

where k – number of time sections, for which predicted and experimental values of the level of parametric reliability were found; $P(t_i)_{pr}$ – predictive value of the parametric reliability level for ED of control sample obtained from (8) for the i-th time point; $P(t_i)_{ex}$ – experimental value of the level of parametric reliability for ED of control sample, calculated by the expression (9) for the i-th time point; $i = 1, 2, \ldots, k$.

The proposed method of predicting the parametric reliability of ED was tested on the powerful BT of KT872A type. Parameters h_{21E} and $U_{CE(sat)}$ were studied as functional. Electrical measurement modes of parameters conformed to the requirements of BT technical documentation. Below as an illustration present the results for the parameter $U_{CE(sat)}$.

For physical modeling of parameter $U_{CE(sat)}$ degradation two samples were formed: training samples in the amount of $n = 200$ specimens and control sample in the amount of $r = 300$ specimens.

Training samples are used for obtaining physical-statistical degradation model $U_{CE(sat)}$. Control samples were intended to evaluate the error of group prediction. In relation to the control samples at the initial time ($t = 0$) the problem of predicting the group parametric reliability for time points t_i (3 840, 8 320, 12 800, and 17 280 h) was solved, and then a physical simulation of operating time with control of parameter $U_{CE(sat)}$ value on time points was performed.

Physical modeling for the degradation of parameter $U_{CE(sat)}$ was to conduct for BT on standard procedures [15–19] of accelerated forced testing equivalent 17 280 hours in terms of the functioning BT in normal operating conditions. To obtain expressions of the form (6), (7) the application Microsoft Excel, the package “Data Analysis” tool “Regression” was used.

Expressions of the form (6) and (7), obtained using the training sample of specimens, for a parameter $U_{CE(sat)}$:

$$m(U_{CE(sat)}\,|t) = 0{,}6417m_0 + 1{,}2745\sigma_0 + 1{,}8088(t)^{0,5}, \quad (11)$$

$$\sigma(U_{CE(sat)}\,|t) = 1{,}1292m_0 - 280{,}08[m\cdot(\sigma_0)^{-1}]^{0,5} + 2{,}1304(t)^{0,5}, \quad (12)$$

where m_0, σ_0 – average value and standard deviation of $U_{CE(sat)}$ at the initial time ($t = 0$).

Values $m(U_{CE(sat)}\,|t)$ and $\sigma(U_{CE(sat)}\,|t)$, determined by the expressions (11) and (12) are the physical characteristics of the statistical model for degradation of parameter $U_{CE(sat)}$.

For the control sample in the amount $r = 90$ specimens by the expression (8) were obtained predicted parametric reliability values $P(t_i)_{pr}$ of BT for operating time t_i. Table II shows the values of the level of parameter reliability for BT, in line with expectations and the experimental observations for several values of norms for parameter $U_{CE(sat)}$, established by the consumer. Condition specified in the figured brackets of expression (1) for time sections t_i was chosen in the form $U_{CE(sat)} \leq U_{norm}$, where U_{norm} – norm for the parameter $U_{CE(sat)}$, specified by the BT consumer.

TABLE II

THE RESULTS OF THE PARAMETRIC RELIABILITY PREDICTION ON THE PARAMETER $U_{CE(SAT)}$ IN BT OF CONTROL SAMPLE

The value of U_{norm}, mV	Probability $P(t_i)$ at time t_i, h:							
	3 840		8 320		12 800		17 280	
	$P(t_1)_{pr}$	$P(t_1)_{ex}$	$P(t_2)_{pr}$	$P(t_2)_{ex}$	$P(t_3)_{pr}$	$P(t_3)_{ex}$	$P(t_4)_{pr}$	$P(t_4)_{ex}$
900	0,781	0,853	0,679	0,735	0,618	0,706	0,576	0,677
1000	0,876	0,883	0,780	0,794	0,715	0,824	0,668	0,735
1200	0,972	0,941	0,917	0,941	0,865	0,912	0,821	0,883
1400	0,996	0,971	0,977	0,941	0,95	0,941	0,920	0,912
1600	0,9997	1,000	0,995	0,971	0,985	0,941	0,971	0,912

Experimental assessment of parametric reliability level of control sample of BT on the parameter $U_{CE(sat)}$ obtained by expression (9). The results of this assessment in the form of probabilities $P(t_i)_{ex}$ made to the Table II. Using data from the Table II, by expression (10) average prediction error Δ_{av} of parametrical reliability for different norm values of parameter $U_{CE(sat)}$ (Table III) was calculated.

TABLE III
VALUES OF THE AVERAGE PREDICTION ERROR Δ_{av}

Value of $U_{CE(sat)}$, specified by the consumer, mV	900	1 000	1 200	1 400	1 600
Average prediction error $\Delta_{av,}$ %	11,26	8,09	4,83	2,40	4,18

Table III shows that the prediction error are acceptable to the practice in time points from t = 0 to $t = t_k$ = 17 280 h.

IV. CONCLUSION

Obtaining physical and statistical degradation models and group prediction on the example of functional parameters for considered BT types (KT872A, KT8272B и KT8271B) confirmed, that the proposed method enables experimentally, using physical modeling of the ED functional parameter degradation and the statistical analysis of simulation results, to obtain physical-statistical degradation model of this parameter. It is found once for considered type of ED by examining of training samples. The resulting physical-statistical degradation model enables to solve the problem of group prediction at the initial time (t = 0) for other samples of the same type of ED.

The solution is to determine the probability of the fact that the ED function parameter will be in the range of specified norms during the time of interest.

REFERENCES

[1] Borovikov S. M. Statistical forecasting for rejection of potentially unreliable electronic products. – M.: “New Knowledge” publishing, 2013. – 343 p.
[2] Borovikov S. M. “Reliability prediction of electronic equipment”/ it was recommended for publication by the university (BSUIR). – Minsk: MSHRC, 2010. – 308 p.
[3] Borovikov S. M. Theoretical foundations of design, technology and reliability: a book for students of engineering specialties. – Minsk: DesignPRO, 1998. – 336 p.
[4] European Organization of the Quality Control Glassary. – Bern: EOQC. 1988. – 24 p.
[5] Physical-statistical models of functional parameters of the degradation electronics products / S. M. Borovikov, [and other] // NAS Reports of Belarus. – Vol. 51, No. 6, 2007. – pp. 105–109.
[6] The reliability prediction of electronic devices based on a mathematical model of functional parameter degradation / S. M. Borovikov, E. N. Shneiderov, [and other] // BSUIR Reports: Electronics, Materials, Technology, Computer Science. – No. 6 (36), 2008. – pp. 32–39.
[7] Borovikov S. M., Shneiderov E. N. The parametric reliability prediction of electronic devices using Weibull distribution // Reports BSUIR. – No. 7 (61), 2011. – pp. 31–37.
[8] Borovikov S. M., Shneiderov E. N. Forecasting method of parametric reliability of electronic devices by model of functional parameter's degradation / Reports BSUIR. – No. 6 (84), 2014. – pp. 5–11.
[9] Borovikov S., Shneiderov E., Burak I. Models Based on the Weibull-Gnedenko Distribution for the Description of the Degradation of Functional Parameters of Electronic Devices / Computational Problems of Electrical Engineering. – Vol. 6, No.1, 2016. – pp. 1–8.
[10] Borovikov, S. M., Beresnevich A. I., Shalak A. V. Prediction of functional parameters of semiconductor devices using degradation models / Modern Radioelectronics: scientific research and personnel training: collection of materials on the results of international scientific and practical conf., Minsk, April 10–11, 2007; ed. by prof. N. A.Tsyrelchuk. – Minsk : MRC, 2007. – Part 1. – pp.105–107.

[11] Beresnevich, A. I. Prediction of the reliability of electronic products using degradation models of functional parameters / Technical means of information protection: thesis of the report VIII of the Belarusian-Russian scientific and technical conf., Braslav, Belarus, May 24–28, 2010. – Minsk: BSUIR, 2010. – p. 70.
[12] Physical and statistical bases of predicting the reliability of electronic products on models of parameter degradation / S. M. Borovikov, [and other] // Modern problems of radio engineering and telecommunications: materials of the 7th international youth scientific and technical conf. RT-2011, 11–15 April 2011, Sevastopol, Ukraine. – Sevastopol: SevNTU, 2011. – p. 429.
[13] Borovikov S. M., Shneiderov E. N. Correlation of products' functional parameters of the electronic equipment in the time points as a basis for predicting parametric reliability / Modern Means of Communication: papers XVI International scientific and technical conf., Minsk, 27–29 september 2011. – Minsk: HSCC, 2011. – p. 81.
[14] Ventcel E. S., Probability theory: a book for higher. tech. universities; 10th edition. – M.: "High school" publishing, 2006. – 575 p.
[15] Quick Logic Reliability Report / pASIC, Vialink and Quick Logic Corp. – Orleans, 1998. – 21 p.
[16] Robinson L. E. Life expectancy in electronic components and the 10th rule / Testing. – No. 1, 1998. – p. 16.
[17] Acceleration Factors SSB –1.003. – Arlington : EIA Government Electronics and Information Technology Association Engineering Department, 1998. − 14 p.
[18] Bipolar Power Transistors Data Book 1998 / TEMIC Semiconductor GmbH. DGT-005-1297, 1997.
[19] Borovikov S. M., Shneiderov E. N., Plebanovich V. I., Berasnevich A. I., and Burak I. A. Experimental research of electronic products degradation / Reports BSUIR. – No. 2 (104), 2017. – pp. 45-52.