Statistical model of passive tag for production processes automation RFID system parametric failures

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Abstract. The main causes of the passive tag for manufacturing automation Radio Frequency Identification System (RFID) parametric failures by the criterion of the minimum range are considered. A mathematical model that allows estimating the yield of passive tags and the reliability during the assigned lifetime by the specified criterion has been developed.

1. Introduction

Radio Frequency Identification Systems (RFID) are widely used in many areas of the economy. They are used in logistics, agriculture, medicine, transport infrastructure, as well as industrial production [1]. In particular, internal logistical tasks for the purpose of integrated automation of production processes at industrial enterprises are successfully solved with the use of RFID [2].

The RFID system for production processes automation in an enterprise includes an information processing center (IPC), a set of reading devices (portals and mobile terminals) located in control zones, and tags mounted on parts, assembly units, finished products or wrapped containers. The reader sends requests over the air automatically or on command. The tag that has entered the reader’s operation zone accepts the request, processes and sends a response containing the identification code of the object it located on. The code received by the reader is sent to the IPC where information of the object, the technological route stage, etc. are processed.

RFID systems with UHF passive tags based on resonant tunneling diodes (RTD) are promising for production automation. Firstly, passive tags do not require an independent power source (accumulator or battery). Its presence can significantly increase its dimensions and weight, as well as reduce durability, especially in harsh operation conditions. Passive tag obtains the power from the energy of the reader’s electromagnetic radiation. Secondly, the UHF RFID system’s maximum range can vary from ones to tens of meters (depending on the conditions of radio signal propagation). Thirdly, the use of RTD based on AlGaAs heterostructures in the power supply system of passive tags can increase their range by up to 3 times compared to tags made using traditional CMOS technology or using Schottky barrier diodes for RF signals rectification [3].
2. Statement of the problem
One of the main characteristics of an RFID system is its range or maximum distance from the tag to the reader which tag’s data can be read at. Reducing of the label range to values below the minimum allowable for any reason will make it impossible to read data from it at a specified distance and should be considered as a parametric label failure. For the RFID automated control and accounting system used in the production process, this means a failure in the automated line which will lead to its downtime and, as a result, time and financial losses for the enterprise.

Thus, the reliability of the RFID tag is the important index, especially in automated production control systems. Numerically the reliability of the tag can be defined as the probability of failure-free operation during the assigned lifetime. Those, the problem of estimating the tag reliability value during an RFID system designing appears. This work is devoted to solving this problem.

3. Solution of the problem
Discussing tag’s reliability in terms of the probability of failure-free operation during the assigned lifetime from the viewpoint of the minimum allowable range ($r_{\text{min}}$) parametric failures, two aspects should be considered:

- the tag’s design parameters technological variation, which is the cause of the range random variation;
- tag’s design parameters degradation with time under the action of destabilizing exploitation factors, as a result of which the range changes.

The first aspect is related to the production of RFID tags and determines the yield of the production process. The second one is associated with the exploitation of tags and causes a model of gradual failures according to the specified criterion.

For RFID systems with passive tags, the range is determined by the ability of the tag to convert the electromagnetic radiation energy of the reader into the DC energy required for its power supply. In the tag, this function is performed by rectenna – a complex of the tag’s antenna and the rectifier of the RF signal. The range of the tag can be determined by the formula:

$$r = \left( \frac{P_{\text{EIRP}} S_{\text{eff}} K_e}{4\pi P_{\text{DC}}} \right)^{1/2}$$  \hspace{1cm} (1)

where $P_{\text{EIRP}}$ is the equivalent isotropic radiated power of the reader's antenna (determined only by the characteristics of the reader); $S_{\text{eff}}$ is the tag’s antenna effective area (determined by the antenna design); $P_{\text{DC}}$ is the DC power consumed by the tag; $K_e$ is the rectenna efficiency coefficient. In [3], it was shown that the rectenna efficiency coefficient depends both on the antenna design and the RF signal rectifier (its electrical circuit), and on the current-voltage characteristic (IVC) of nonlinear elements (RTD) that are parts the rectifier. In turn, the IVC of the RTD optimized for the rectification of RF signals is determined by the parameters of its design: physical dimensions and chemical composition of the structural elements. Considering that the characteristics of the reader, the design of the antenna and the rectifier and the power consumption of the tag remain unchanged during the entire lifetime, it can be concluded that the range of the tag will depend only on the parameters of the RTD design.

3.1. Technological variation of RTD design parameters
In the general case, RTD consists of a semiconductor resonant tunneling structure (RTS), as well as top and bottom ohmic contacts. The characteristic planar dimensions of these areas are ones of micrometers. At the same time, the thickness of the RTS is a fraction of micrometers, and the thickness of its individual layers does not exceed 10 nm. However, it is the thickness and chemical composition of the RTS layers that determine the nonlinear properties of the RTD.
The main characteristic of the RTD is its IVC, i.e. dependency $I_{RTD}(U_{RTD})$. The simplified equivalent circuit of the RTD can be represented as a series connection of the nonlinear resistance $R_{RTS}$ and the active parasitic resistance $R_P$ (see figure 1). Thus, the IVC of the RTD will be determined by the sum of the nonlinear resistance of the RTS and the parasitic active series resistance.

$$R_{RTS} \quad \quad R_P$$

**Figure 1.** The simplified equivalent circuit of the RTD.

Nonlinear resistance of the RTS can be described as:

$$R_{RTS}(U_{RTS}) = \left[ A_{RTS} \frac{dJ(U_{RTS})}{dU_{RTS}} \right]^{-1}$$  \hspace{1cm} (2)

where $U_{RTS}$ is the voltage on the RTS; $A_{RTS} = f(a)$ is the area of the RTS that is a function of the RTS linear (planar) dimensions vector $a$; $J(U_{RTS})$ is the current density passing through the RTS that is a function of the vector of parameters $g$ including the thickness and chemical composition of the RTS layers. The dependence of the current density through the RTS on the voltage is determined by its quantum-mechanical properties and can be described by various models [4].

Parasitic active resistance is the sum of the resistances of the top and bottom ohmic contacts generally having different linear dimensions $b_T$ and $b_B$, as well as specific contact resistances $\rho_T$ and $\rho_B$.

Thus, the IVC can be represented as a function of the vector of RTD design parameters:

$$I_{RTD}(U_{RTD}) = f(\varphi)$$  \hspace{1cm} (3)

where

$$\varphi = \{a, g, b_T, b_B, \rho_T, \rho_B\}.$$  \hspace{1cm} (4)

Considering (1), as well as the rectenna model described in [3], general view of the RFID passive tag power supply system model can be represented as

$$r = f\left(P_{EIRP}, S_{EFF}, P_{DC}, R_A, N_D, \varphi \right)$$  \hspace{1cm} (5)

where $R_A$ is the input impedance of the antenna; $N_D$ is the number of RTD in the rectifier. The input parameters of the model are the design parameters of the tag and the characteristics of the reader, the output parameter is the range of the tag.

Accounting for the technological variation of the RTD design parameters is implemented by representing the elements $\varphi_i$ of the RTD parameters vector $\varphi$ as random variables characterized by the corresponding probability density functions $f_i(\varphi_i)$. The type of distribution for each random variable depends on the technological process of making the RTD structural element characterized by the corresponding parameter. Thus, the output parameter of the model (5) is also a random variable distributed according to some law $f(r)$:

$$f(r) = f\left[ P_{EIRP}, S_{EFF}, P_{DC}, R_A, N_D, \{f_i(\varphi_i)\} \right], \quad i = 1...N$$  \hspace{1cm} (6)

where $N$ is the number of the RTD design parameters and $\{\}$ denotes the vector of density functions.

Then the yield according to the criterion of the minimum allowable range $r_{min}$ is determined by the formula
The probability of failure can be defined as

\[ P_f = 1 - Y. \] (8)

### 3.2. Degradation of the tag design parameters

The tag is exposed to a number of environmental factors affecting the parameters of its design during exploitation. As a rule, their effect leads to a decrease in the tag’s functions. This paper discusses the effect of high temperature as the main destabilizing factor reducing the range of the RFID tag.

The negative effect of high temperature on the RFID tag during operation is primarily associated with diffusion processes in semiconductor devices which speed increases exponentially with temperature increasing. Particularly, in a RTD, diffusion processes proceed both in the RTS region and in the region of ohmic contacts, leading to a change in its IVC. Using the simplified RTD model (see figure 1), one should speak of the change, firstly, of the nonlinear resistance of the RTS \( R_{\text{RTS}} \), and secondly, of the parasitic resistance \( R_p \) as the sum of the top and bottom ohmic contact resistances.

The studies carried out by the authors showed that the change in nonlinear resistance of the RTS is negligible compared with the change in resistance of the ohmic contacts of the RTD under the action of high temperature (up to 300 °C). The authors also obtained an empirical dependence of the specific contact resistance on temperature \( T \) and time \( t \) and determined the parameters of this dependence for some types of RTD and ohmic contacts [5]. In relation to the considered model of the passive tag power supply system (5), the following relationship can be written:

\[ \rho_{T,B} (T,t) = \rho_{T,B,0} + \chi \cdot \exp \left[ -E_A (2k_B T)^{-1} \right] \sqrt{t} \] (9)

where \( \rho_{T,B} \) is the specific contact resistance of the top and bottom ohmic contacts, respectively; \( \rho_{T,B,0} \) is the specific contact resistance of the top and bottom ohmic contacts, respectively, at the initial time (immediately after manufacture); \( \chi \) is a coefficient depending on the design and technology of the ohmic contacts; \( E_A \) is the activation energy of diffusion processes in ohmic contacts; \( k_B \) is the Boltzmann constant.

### 3.3. Tag’s probability of failure-free operation

Taking into account the model of degradation of the RTD ohmic contacts (9), the statistical model of the RFID passive tag power supply system (6) is transformed to:

\[ f(r,t) = f \left[ P_{\text{ERP}}, S_{\text{EFF}}, P_{\text{DC}}, R_N, N_D, t, T, \{ f_i(\varphi_i) \} \right], \quad i = 1...N. \] (10)

Here \( f(r,t) \) is the surface in the coordinates \((r,t,D)\), where \( D \) is the probability density. The cross section of a given surface at the point \( t_i \) is a probability density function of the RFID tag range distribution after its exploitation during the time \( t_i \).

The authors analyzed the statistics of the tag failures during its exploitation according to the criterion of the minimum range using the obtained model. The analysis was carried out by the Monte Carlo method. The resulting distributions of the RFID system range are well described by the Weibull law [6]. Typical diagrams of RFID system range probability density functions during exploitation are shown on figure 2. It is easy to see that the area of the figure bounded by the curves and the abscissa axis in case of \( r < r_{\text{min}} \) increases with time. This means that the probability of the tag’s failure \( P_f \) grows, i.e. there is a degradation of the main parameters of the tag power supply system during exploitation, that is caused by changes in the design of the RTD.
Figure 2. Probability density distribution of $r$ after exploitation during $t_0$, $t_1$ and $t_2$ ($t_0<t_1<t_2$).

Thus, using (10), the tag’s reliability in terms of probability of failure-free operation during the lifetime $t_L$ by the criterion of the minimum range can be defined as

$$
R(t_L) = 1 - P_F(t_L) = 1 - \int_{r_{\text{min}}}^{r_{\text{max}}} f(r, t_L) \, dr = \int_{r_{\text{min}}}^{r_{\text{max}}} f(r, t_L) \, dr.
$$

(11)

4. Conclusion

In conclusion, consider the key features of the developed model of RFID passive tag parametric failures. Using the information about technological variation of RTD parameters in the manufacturing process, as well as characteristics of degradation processes in their structure, the model allows to evaluate not only the reliability indexes of passive tags based on RTD, but also the yield in the manufacturing process according to the tag range as one of the most important functional indicators of RFID system. Obviously, this model does not cover the reliability indexes of all the RFID system components. However, it can be a part of the complex RFID system reliability model which will allow for a more accurate estimation of system reliability at the design stage.

It is also worth noting that this model can be used for RTD based passive tags design and technological optimization with the criteria of maximum yield and the probability of failure-free operation during a given lifetime [7].

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