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Reliability of Semiconductor Converters of Temperature and Humidity of Disperse Media with Respect to Catastrophic Failures

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ABSTRACT: The results of a study of the reliability of a semi-conductor transducer of temperature and humidity of dispersed media with respect to a catastrophic failure are presented. It has been established that catastrophic failures occur for a semiconductor converter with a constant current value and power release in the region of the *p-n* junction. The reliability of the transducer during pulsed operation, i.e. the probability of the absence of catastrophic failures at a given mode of operation during the time *t* is determined by the exponential distribution law.

I. INTRODUCTION

In the information-measuring technology, semiconductor converters of humidity and temperature of various media are widely used, which is explained by a number of their positive properties, such as measurement accuracy, reliability, manufacturability, simplicity of design and linearity of the static characteristic.
The development of high-speed and accurate nano - transducers of various physical quantities using doping of active semiconductor materials, increasing the linearity of the static characteristics and improving the technology are carried out a variety of research projects related to the introduction of transition elements in silicon semiconductor structures, that is characterized by the creation of new, sensitive and efficient semiconductor converters, which are the main task of semiconductor microelectronics [1, 2].

To obtain an effective thermal sensor based on a compensated semiconductor with a maximum coefficient of temperature sensitivity, it is necessary to use a highly compensated semiconductor. The experiment confirms that the more compensated the material, the greater the coefficient of temperature sensitivity. At this specific resistivity, thermistors based on a highly compensated semiconductor -type will be somewhat less sensitive than on the basis of ann-type semiconductor [3, 4].

With equal specific resistances, the hole concentration in a semiconductor is of a type higher than the concentration of electrons in an n-type semiconductor due to the lower hole mobility compared to electrons. A higher concentration of charge carriers in a type-of semiconductor leads to a smaller depth of the Fermi level, and therefore to a lower coefficient of temperature sensitivity, with the same values of resistivity [5].

When using a thermal sensor is included in the bridge circuit, the bridge is usually powered by a current or voltage source. With an increase in the temperature of the medium, the resistance of the measuring thermal sensor decreases, this leads to an increase in the dissipated power at the thermal sensor, which in turn leads to a greater heating of the thermistor with its own current [6].

Therefore, at high temperatures and low nominal resistance, the temperature of the thermistor will differ from the temperature of the medium, i.e. a thermistor will measure some effective temperature different from the true temperature. To avoid this, it is necessary to use thermistors based on a material with high resistivity, i.e. based on highly compensated silicon with a specific resistance of 10^4 to 10^5 *Om*sm*.

The reliability of a semiconductor transducer for temperature and humidity of dispersed media, developed by using doping of transition elements of a semiconductor structure, is considered below.

It is known that failures in measuring devices and systems occur randomly, therefore they are random events, but the reasons for the occurrence of a failure are associated with certain physical and physic-chemical processes occurring in the measuring converters, materials and structures during its operation. The choice of the approach to the determination of reliability by the methods of the physics of failure is determined by the assumption that the physical processes and chemical reactions occurring on the surface and inside the measuring device cause deterioration of its electro-physical characteristics and, as a result, catastrophic and parametric failures.

The failure of any element and measuring device can be determined by the action of the following factors:

- external influences - the action of thermal, mechanical and electrical loads;
- the flow of a set of physicochemical processes that are most significant on the surface or in the vicinity of defects on the volume of the product;
- structural imperfections of the source materials of the product, due to the presence and impurities, dislocations and concentration gradients;
- constructive-technological imperfections of the production process of elements of measuring systems.

It is obvious that failures of information-measuring devices arise when their strength, which is laid when they are designed in production, will be lower than the load acting on them during operation, considering that the output of the electrical parameter beyond the tolerance is also called the predominance of the load over the strength [7, 8].

II. RESEARCH OUTCOMES AND DISCUSSIN

In this case, the probability of failure of the information device due to the violation of its mechanical, electrical and thermal strength due to the corresponding type of load [9]:

$$q = f(\Delta x_1, \Delta x_2, \dots, \Delta x_u), \tag{1}$$

where $\Delta x_i = \bar{x} - x_1$ - safety factor of the semiconductor converter for the corresponding type of load; $\bar{x} -$ is the mathematical expectation of the maximum permissible value that determines the appearance of a converter failure; x_1 −effective (working) load value.

The materials used in the elements of semiconductor converters can be divided into insulating, conductive, contact and structural. The process of failure of a semiconductor converter is a kinetic process, the internal mechanism and speed of which is determined by the structure and properties of the element of a semiconductor converter.

In [10], a classification of failures of technical (facilities) devices according to physicochemical processes and conditions of the processes in the elements is proposed. This classification is carried out according to the following features: by the type of material of the element; the place of the processes affecting the performance; by the type of energy that determines the nature of the process; the type of operational impact on the nature of the process.

There are processes occurring in the volume of the element material, on the surface of the elements, in electrical circuits, associated with the mutual influence of elements. To classify failures by type of energy, they release energy: mechanical; electric; chemical; electromagnetic; annihilation [11].

Operational impacts are classified according to the following criteria: environmental impact and impacts arising only in the conditions of active element operation; the nature of the impact on materials of the environment and the working environment; according to the type of measurements caused by influencing factors in the material. According to the nature of time measurement, two types of operational effects are distinguished: disturbances that after their occurrence remain gradual or change regularly, and effects that are random functions of time [12].

Reliability The majority of information converters with distributed parameters is largely determined by the reliability of electrical insulation. Under the action of electric and magnetic fields, elevated temperature, mechanical stresses, environmental influences, necessary measurements of the chemical composition and properties of electrical insulation occur, the so-called aging takes place.

Cyclic changes in the electric field acting on the molecules and shells of atoms, cause ionization, additional losses of electrical energy and strong heating of the material. This process is accompanied by significant electrochemical electrolysis processes, electrical corrosion of the dielectric. The main characteristic of the insulation, which determines the reliability of the semiconductor temperature converter, is its electrical strength. However, this property can be preserved in the course of operation only if the following qualities are present: high thermal conductivity, mechanical strength, stability of the chemical composition and insulation structure [13, 14].

Magnetic field at the same time creates mechanical stresses in materials, especially in ferrites and ferromagnets. The basis of the reactions, leading to irreversible chemical changes in the composition of the instructors, is the oxidative stress destruction in materials, especially in ferrites and ferromagnets. The basis of the reactions leading to irreversible chemical changes in the composition of the instructors, is oxidative destruction.

For the manufacture of semiconductor sensors of various physical quantities, mainly monocrystalline silicon, germanium phosphide and gallium arsenide are used. The manufacturing techniques of semiconductor sensors make it possible, using the properties of semiconductor materials, to build epitaxial layers of semiconductor material, diffusion of dopants of transition metals and vacuum deposition of conductive films to produce both active and passive elements in the bulk and on the surface of a single piece of semiconductor material. Consider the reliability of a semiconductor temperature converter ® with respect to a catastrophic failure. Catastrophic (sudden) failures of a semiconductor temperature transducer are characterized by a violation of mechanical, electrical and thermal strength. As shown by experimental studies, the distribution of the critical parameter for a semiconductor converter, which determines its mechanical strength, electrical and thermal, obeys the normal law (Gauss) distribution. The failure rate in violation of mechanical, electrical and thermal strength in general, where is determined by the expression in the form [15, 16].

$$\alpha = \frac{dq}{dt} \cdot \frac{1}{p} = \frac{dq}{dt} \cdot \frac{1}{1-q}, \tag{2}$$

or at $p \to 1$ with sufficient approximation

$$\alpha = \frac{dq}{d(\Delta)} \cdot \frac{d(\Delta)}{dt}, \tag{3}$$

where $\Delta -$ Difference between the current and average limit value (x0 m) of the temperature θ_0 of the semiconductor converter.

When the violation of mechanical strength is mainly influenced by physicochemical processes, it has [17]

$$\theta_p = P_0 + \Delta P, \tag{4}$$

where P_0- applied force.
Since the change in cross-sectional area ΔS at $S = S_0 - \Delta S$ obeys Dependencies [17],

$$\Delta S = b \cdot \Delta h = c_1 \cdot e^{\alpha \cdot \Delta\theta} \cdot e^T, \tag{5}$$

where $\Delta\Theta$ – temperature increment; $\alpha = \frac{k}{T}$ – coefficient; $\delta = 0{,}5 \div 1$ – coefficient, then

$$\Delta\Theta_p = C_2(\exp \alpha.\Delta\Theta)t^T \qquad \textit{and}$$

$$\frac{d(\Delta\Theta)}{dt} = -\frac{d(\Theta_p)}{dt} = \delta.c_2 e^{\alpha\Theta}.t^{r-1}, \tag{6}$$

where $\Delta\Theta = c_2 \frac{P_0}{S_0}$.

Hence the failure rate in violation of mechanical strength caused by the influence of the physic - chemical process, is determined [18],

$$\alpha = \alpha_{0n}.e^{\alpha\Delta\Theta}.t^{r-1}. \tag{7}$$

Similarly, in violation of the electrical, durability of the floor temperature converter under the influence of physic - chemical processes

$$x_p = \frac{u}{d_0 - \Delta d} = E_p - E_p \frac{\Delta d}{d_0} = E_p - \Delta E_p, \tag{8}$$

or $\Delta x_p = \Delta E_p = E_p \frac{\Delta d}{d_0}$,

where E_p – electric field strength; Δd – change the thickness of the considered part of the converter.

Since the change in the working thickness of the semiconductor converter obeys the dependence [19],

$$\Delta d = c_1^d e^{\alpha_1 \Delta\Theta}.t^r,$$

where $r = 0{,}5 \div 1$ and $\alpha_1 = -\frac{k}{T}$, then consequently

$$\Delta x_p = c_1^1 e^{\alpha_1 \Delta\Theta}.t^r,$$

where $c_2^1 = c_1^1 = \frac{E_p}{d_0}$.

Hereof $$\frac{d(\Delta x)}{dt} = -\frac{d(\Delta x_p)}{dt} = \gamma_1.c_2^1 e^{\alpha_1\Delta\Theta}.t^{r-1}.\gamma. \tag{9}$$

The failure rate of a semiconductor converter caused by this process is defined as

$$\alpha = \alpha_{0el}.e^{\alpha_1 \Delta\Theta}.t^{r_1 - 1}. \tag{10}$$

With a sharp increase in the temperature of the semiconductor converter, there are violations of the thermal strength of electrical components. Catastrophic failures occur for a semiconductor converter with a constant current value, when the balance of power allocated at the $p - n$ junction is equal to the power discharged to the environment [20, 21],

$$\frac{J^2 p_0 \, \Delta l}{S} e^{\alpha_0 \Delta\Theta} = MS_1 . \Delta\Theta,$$

or $$e^{\alpha_0 \Delta\Theta} = \left[\frac{MS_1}{p_0 \, \Delta e \, J^2} \left(S_0 - \Delta S \right) \right]^{\Delta\Theta} = K_S \, \Delta\Theta, \tag{11}$$

where $\alpha \geq 0$ temperature coefficient of resistance change; $S - \Delta S -$ reducing the crossectional area of the transducer:

$$\Delta S = c_0 . e^{\alpha \Delta\Theta} . t^r .$$

For this case, the temperature value to the ratio

$$a . e^{\alpha \Delta\Theta} = K_S ,$$

after which there is an unlimited increase in temperature to a value of θ_{kr} and there is a violation of the thermal strength of the semiconductor temperature converter.

Based on the above, we note that the failure rate due to the violation of the thermal strength of the semiconductor converter is defined as.

$$\alpha = \frac{dq}{d(\Delta\theta)} \cdot \frac{d(\Delta\theta)}{dt} = \left[\frac{1}{\delta_0 \sqrt{2\Pi}} \exp\left(\frac{\theta - \theta_{kr}^2}{2\delta_0^2} \right) \right] \frac{d\theta}{dt}. \tag{12}$$

Since the scatter s value in θ, due to the scatter of the values of d_Θ and K_S obeys the normal distribution law.

The probability of the absence of catastrophic failures (reliability) under this mode and operating conditions during the time t is defined as

$$P_\alpha = e^{-\int_0^t \alpha_\Sigma(t) dt}, \tag{13}$$

where $d_\Sigma -$ the total failure rate of the circuit.

At $d_\Sigma(t) \neq const$ the reliability value of a semiconductor converter can be expressed according to the Weibullaw

$$P_\alpha = e^{-\frac{(\delta + t)^2}{\alpha}}, \tag{14}$$

and at $d_\Sigma(t) = const$ we get the exponential distribution

$$P_\alpha = e^{\alpha_\Sigma t}. \tag{15}$$

Consequently, the reliability of a semiconductor converter in a pulsed mode of operation, that is, the probability of the absence of catastrophic failures under a given mode and operating conditions during the time t is determined by the exponential distribution law.

$$P_\alpha = e^{-t\left(\alpha_1 \frac{\tau_1}{\tau_1 + \tau_2} \right)} . \, e^{-t\left(\alpha_1 \frac{\tau_2}{\tau_1 + \tau_2} \right)} . \, e^{-t\alpha_3} = e^{-\left(\alpha_1 \frac{\tau_1}{\tau_1 + \tau_2} + \alpha \frac{\tau_2}{\tau_1 + \tau_2} + \alpha_3 \right) t}, \tag{16}$$

where τ_1 - is the signal duration; τ_2 - the duration of the pause;

α_1-failure rate when the semiconductor converter state is in continuous operation in the operating mode;

α_2-failure rate with continuous stay of the state of the semiconductor converter outside the operating mode;

α_3-an additional magnitude of the failure rate due to transients when the semiconductor converter is turned on and off into a measurement circuit.

III. CONCLUSION

Thus, the failure rate is significantly affected by the temperature variation inside the device in this mode of operation and in conditions that are characterized by a sharp violation of the thermal strength of electrical components. It has been established that catastrophic failures occur for a semiconductor converter with a constant current value and power release at the *p-n* junction section. Reliability of a semiconductor converter with a pulse mode of operation, i.e. the probability of the absence of catastrophic failures at a given mode of operation during the time *t* is determined by the exponential distribution law.

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