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Modeling the process of fitting thick-film resistors by the method of flare discharge

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Abstract. The procedure of mathematical modeling of the process of fitting thick-film resistors of hybrid integrated circuits by the method of flare discharge is presented. A device is described that provides the fitting of resistors with a specified accuracy. A mathematical expression is obtained that relates all the physical and geometrical parameters of the system "discharge-resistor-substrate" and the technological parameter. The recommendations for increasing the stability of the resistors after fitting are developed.

1. Introduction

At present, thick-film resistors, including precision ones, are widely used for manufacturing microassemblies with irregular structures. The existing methods of manufacturing thick-film resistors do not provide the required accuracy of the nominal values of resistance. To ensure its accuracy, a resistance fit is used. The most common is laser adaptation of the resistance of thick-film resistors by removing part of the resistive layer. However, in this case, it is not always possible to achieve the necessary stability of the resistors. In addition, laser fitting is expensive compared to cheap technology for manufacturing thick-film resistors. These factors require the development of a cheaper fitting method, which ensures a high stability of resistor resistances.

In [1], it was reported about the fitting of thin-film resistors by a relatively simple and cheap method of flare discharge. Such a fitting introduces a small perturbation in the parameters of the resistors; the air temperature in the flare discharge channel does not exceed 4500K. Moderate temperature in the fitting zone favorably affects the properties of the resistors. The heat sources in such a fitting are concentrated in one discharge channel, in contrast to, for example, a crown discharge, when the heat sources are distributed over several channels. This makes it possible to achieve high fidelity accuracy (0.01%).

The flare discharge is one of the types of high-frequency one-electrode electric discharge. The free flare discharge is a plasma formation with a brightly defined channel and envelope. As a rule, it occurs at frequencies above 5 MHz [2, 3] and it is easily ignited on sharp electrodes with large steepness, thin wires, etc. The temperature of the flare discharge at various points is different and varies from 2000 K at the shell boundary to 4500 K near the electrode. Its structure is determined by the power introduced into the discharge, the type of the surrounding gas and the frequency of the feeding field. The main parameters of the flare discharge are determined by means of an electrodynamic model, for which the discharge is represented in the form of a column of plasma along which a plane inhomogeneous transverse-magnetic wave propagates [4].
2. **Power of the discharge source**

The most important parameter of the discharge source is power. To determine the required power, a physical model for the interaction of a flare discharge with a thick film was developed. The radiation incident on the surface of the opaque film is partially reflected, partially absorbed by the surface layer. Absorption of energy leads to local heating.

In the first approximation, we can assume that the interaction of the flare discharge on the film from the energy point of view is equivalent to the action of laser radiation. Then the surface in the treatment zone is heated to the evaporation temperature in a time $t_n$, determined from the relation

$$ t_n = \frac{\pi}{4} \gamma c W^2 (T_e - T_0)^2 $$

where $\lambda$ is the thermal conductivity of the film substance; $c$ - body capacity; $\gamma$ is the film density, kg/m; $W$ is the radiation flux density; $T_e$ - evaporation temperature of the film material; $T_0$ is the initial temperature of the film.

The density of the discharge radiation flux can be written as follows:

$$ W = \frac{\pi}{4} \gamma c W^2 (T_e - T_0)^2. $$

On the other hand, the flux density can be determined through the channel cross-section:

$$ W = \frac{P}{S}, $$

where $P$ is the power of the flare discharge, W; $S = \pi r^2$ - the cross-sectional area of the discharge channel, mm$^2$; $r$ - radius of the discharge channel, mm.

The power of the flare discharge is

$$ P = P_1 \eta, $$

where $P_1$ is the generator power, W; $\eta$ - generator efficiency.

The power of the generator can be written as follows:

$$ P_1 = \frac{P}{\eta} = \frac{WS}{\eta} = W\pi r^2/\eta $$

Formula (1) allows us to estimate the required power of the discharge source. It is primarily determined by the characteristics of the material of the resistive layer - $\lambda$, $c$, $\gamma$, $T_n$. The larger the product $\lambda c \gamma$, the higher the power of the source. Therefore, the power $P_1$ will be determined mainly by the characteristics of the conductive components of the resistive layer - in this case copper, palladium and silver.

The values of $r$ and $t_n$ are chosen based on the required and reasonable values of labor and accuracy of adjustment.

Assume that $t_n = 6 \times 10^{-2}$s, and $r = 0.2 \text{ mm}$, $\eta = 0.6 ... 0.7$. Then $P_1 = 30 ... 35$W.

3. **"Electrodynamic model" of the discharge**

According to this "electrodynamic model" a damped transverse-magnetic wave propagates along the channel of the high-frequency flare discharge (HFFD). It is assumed here that its reflection at the end of the discharge channel is unimportant, and it can be neglected. In this case, the distribution of electric currents in the channel of the HFFD has the form [4-6]:

$$ I = I_0 e^{jz\gamma}; \quad \gamma = \alpha + j\beta $$

where $\gamma$ is the complex coefficient of propagation of the electromagnetic wave (wave number) along the discharge channel.

The authors of [7] carried out an analysis of the electrodynamic model and established that in the general case the problem of finding the distribution of electric currents in the radiator from the measurements of the field created by it is quite complex, and its solution was mathematically developed [8] only for the analysis of field components in the far radiation zone. However, its approximate solution is easy to obtain, based on this or that numerical method of calculating the Kirchhoff-Huygens integral.

It is shown that, in accordance with the trapezium method, the approximate value of expression (2) can be written in the form [9]:

$$ I = I_0 e^{jz\gamma}; \quad \gamma = \alpha + j\beta $$
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\[ H_\phi(z) = \frac{1}{4\pi} \int_0^L \left[ \frac{jk_y l(z') e^{-jkr'}}{r'^2} + \frac{y l(z') e^{-jkr'}}{r'^3} \right] dz' = \int F(z'; r'; y) dz' \approx \]

\[ \approx \frac{1}{\Delta z} \left[ \frac{1}{2} \left[ F(z') + F(z_n') \right] + F(z_1') + \ldots + F(z_{n-1}') \right] |y = \text{const.} \]

They revealed the shortcomings of the electrodynamic model. The main one is the lack of consideration of the reflected electromagnetic wave.

4. New electrodynamic model

In the new model, the finiteness of the length of the channel of the HFFD is taken into account. In the case of a theoretical analysis, this is primarily due to the presence of a reflected electromagnetic wave in the discharge channel [10].

A wave of electric current propagating along a line of finite length was considered. In general, the current flowing along a line of finite length is determined [9] as follows:

\[ I(z) = I_0 e^{jz} \cdot e^{-j\gamma z} + c e^j \cdot e^{-j\gamma z} \cdot e^{jt} \]

here \( I, I_0 \) are complex amplitudes of high-frequency currents, respectively at the points \( z \) and \( z = 0 \); \( \gamma = \alpha + j \beta \) is the complex propagation coefficient (wave number) of the electromagnetic wave in the channel of the HFFD; \( ce^j \) is the complex reflection coefficient of the electromagnetic wave at the end of the line.

For a high-frequency current propagating along a line of finite length, we obtain an expression for the effective value of the current:

\[ |I| = |I_0| \sqrt{[e^{j\alpha z} \cos(\alpha - \beta z)]^2 + [e^{j\alpha z} \sin(\alpha - \beta z)]^2} \]

The power integral for the case \( C = 1, \varphi = 0 \) is written as follows:

\[ W = 2 \sigma^{-1} |I_0|^2 \int_0^L \left( \sin^2(\beta z) \right) dz \]

The power dissipating in the HFFD channel was found by integrating expression (3):

\[ W(L) = 2 \sigma^{-1} |I_0|^2 \left[ \frac{ch2az - \sin^2(\beta z)}{2\alpha} + \frac{1}{4\beta} \sin(1) \cos(\beta L) - \frac{L}{2} \right] \]

5. The device of adjustment of film resistors

Due to the low stability of the discharge, the resistive material in the cutting zone does not always penetrate to the full depth. An unstable phase of the material forms. In addition, the manual process of adjustment is laborious and difficult to control.

In this paper, the task was to increase the stability of the flare process and, consequently, the reproducibility of the resistor parameters. The means for achieving the set goal is the developed installation for adjustment (Figure 1).

The installation functions as follows. The motors move the working electrode over the substrate by moving the tables. To measure the displacement of tables along the X and Y axes, photodetectors are designed. The control unit compares the set value of the movement with the "spent" and gives the "Stop" signal for the engine commutation circuit when the set and traversed distances are equal. The switching unit makes the switching of the motors depending on the chosen direction of travel and the initial coordinate. The same unit stops engines on the command of the operator or automatically on a signal from the block / board. The kinematic schemes of displacements along the X and Y axes are identical. Loft in the drive coupling does not affect the accuracy of the "working off" movements; The sensor of the displacement is rigidly connected to the micrometer screw.

Let's consider in more detail the operation of the control unit. The signal coming from the photosensors is amplified and fed to the pulse former, which forms the rectangular waveforms necessary for the operation of the counters. The counters are pre-recorded with the values of the required movement. With the arrival of a pulse, the number written in the counter decreases by one, and after writing zero, the counter gives a pulse to the coincidence circuit and to the next counter, after which it is filled to the value "9". The coincidence circuit gives one of the amplifiers a logical unit
level under the condition of simultaneous arrival at its inputs of pulses of the transition through the "O" from the counters. To stop the movement in the circuit of motor commutation, a signal is sent from the relay. In turn, to activate the relay, it is necessary to amplify the signal of the coincidence circuit.

**Figure 1.** Installation for adjustment: 1 - discharge generator; 2 - coordinate table; 3 - engines; 4 - photosensor; 5 - control unit; 6 - switching unit; 7 - working electrode; 8 - substrate with a resistor; 9 - substrate holder; 10 - vibrator; 11 - resistance meter.

The adjustment was performed at a discharge power of 30 ... 100 W. At the same time, the speed of moving the working electrode relative to the resistor was 5 ... 20 mm / min, and contacting the working electrode with the adjustable resistor was carried out at a frequency of 20 ... 100 Hz. To select the parameters of the fitting mode, a mathematical model was used [11].

It should be noted that the stability of the torch-arc discharge is substantially higher than that of a purely flare discharge. Stabilization of the discharge also enhances the discharge power to 100W. Accordingly, the controllability of the process of adjustment and the reproducibility of the resistor parameters is increased.

However, our studies have shown that the stability and stability of the fitting process in some cases is low. In this connection, the task was set of constructing mathematical models for the distribution of the gas temperature along the axis of the flare discharge channel in the fitting and interaction of a discharge with a film element. Such problems were described in [11, 12]. In this paper, we will consider obtaining working models.

### 6. Model of distribution of gas temperature during fitting

The heat balance equation can be written in the following form:

$$\frac{\partial}{\partial z}(\lambda(T) \frac{\partial T_z}{\partial z}) = aEz \sum_{n=0}^{\infty} \left( \frac{bT_z}{n!} \right)^n - 2\rho R \cdot C \cdot V \cdot \frac{\partial T_z}{\partial z} -$$

$$- \varepsilon C_0.2\pi R_{0}\varepsilon \cdot \cdot 10^{-8}(T_0 - T_{0z}) - \rho \cdot hS_{0z} \cdot \{L_{0z} + C_{0z}(T_{0z} - T_0)\} \ast$$

$$\ast (1 + k_{HR}) + [(L_{HR} + C_{HR}(T_{HR} - T_0))(1 + k_{HR} + k_{HR})] +$$

$$2\pi d T_0 \ln \frac{4c}{R_{HR} + R_{HR}} \cdot \{C_{HR} \cdot R_{HR} - R_{HR}\} \ast$$

$$\lambda_{HR} - \rho R \cdot C \cdot (R_{HR} - R_{HR}) \ln \frac{4c}{R_{HR} + R_{HR}} .$$

To solve the above-described differential equation with respect to $T_z$, general methods for solving such equations are applied. The solution is represented as a sum of general and particular solutions. When finding the particular solution and the coefficients in the general solution, the temperature data considered to be known is used; $T_0$ is the temperature at the initial point at the base of the flame and $T_0$.
at the point \( Z_0 = h + h_n \). Omitting detailed calculations of the search for solutions, the final form of the distribution of \( T_z \) along the \( Z \) axis in a form convenient for perception:

\[
T_z = A \cdot e^{\alpha z} + B \cdot e^{-\beta z} + C
\]

where

\[
A = \frac{T_0 e^{(h + h_n)} \sqrt{\left(\frac{2 \rho_a C_a V_Z}{\lambda_\phi}\right)^2 + \sqrt{4abE^2 - 2 \rho_a C_a V_Z \lambda_\phi}} - T_0}{e^{(h + h_n)} \sqrt{\left(\frac{2 \rho_a C_a V_Z}{\lambda_\phi}\right)^2 + \sqrt{4abE^2 - 1}}};
\]

\[
B = \frac{T_0 e^{(h + h_n)} \sqrt{\left(\frac{2 \rho_a C_a V_Z}{\lambda_\phi}\right)^2 + \sqrt{4abE^2 - 1}}}{e^{(h + h_n)} \sqrt{\left(\frac{2 \rho_a C_a V_Z}{\lambda_\phi}\right)^2 + \sqrt{4abE^2 - 1}}};
\]

\[
C = \frac{2\pi \cdot z \cdot T_0 \ln \left(\frac{4h}{(R_{hh} + R_{hh})}\right)}{abE^2 \left(\lambda_R - C_R \rho_R (R_U + R_H)\right) \ln \left(\frac{4h}{(R_U + R_H)}\right)} - \frac{1}{\epsilon} + \frac{2\pi \cdot C_R \cdot R_{HH} \rho_R \cdot \varphi \cdot L (T_0^4 - T_0^4)}{ab \cdot 10^8 E^2} + \frac{C_R (T_U - T_H) \left(1 + K_H\right) + (1 + K_H + K_{HH})}{(L_{HH} + C_R (T_H - T_H))}.
\]

\[
\alpha = \sqrt{\left(\frac{2 \rho_a C_a V_Z}{\lambda_\phi}\right)^2 + \sqrt{4abE^2 - 2 \rho_a C_a V_Z \lambda_\phi}}; \quad \beta = \sqrt{\left(\frac{2 \rho_a C_a V_Z}{\lambda_\phi}\right)^2 + \sqrt{4abE^2 - 2 \rho_a C_a V_Z \lambda_\phi}}.
\]

7. Model of interaction of the HFFD with the element

We omit the intermediate formulas and equivalent transformations. We get the final expression:

\[
\rho_P e^{\frac{z}{\lambda_{HH}^0 (i)}} = G_1 R_u^2 + G_2 + 8\pi 10^6 \sqrt{\frac{bl^3 \alpha^0 e^{\alpha^0 l}}{G_1 R_u^2 + G_2}}
\]

where

\[
G_1 = \frac{\pi h \rho_k}{t} \left[L_n + A_j \left(1 + k_{HH} \rho_m \rho_k \right) \right] + \left(L_n + A_j \left(1 + \rho_m \rho_k \right) \right] + \frac{\pi h \rho_k}{t} (L_n k_{HH} + A_j) \left(k_{HH} + k_{HH} \right) + R_u^2;
\]

\[
G_2 = \frac{2\pi h}{t} \rho_k \left(C_R \rho_R k_e A_j \right) \frac{1}{\lambda_R + C_R \rho_R k_e A_j}.
\]

The peculiarity of the obtained expression (4) is that it connects all the physical and geometrical parameters of the HFFD-film-substrate system and the technological parameter \( l \).

Using the expression obtained, one can find the dependencies of various parameters on the entire set of parameters of the interacting system.
Thus, by solving (4) with respect to $l$, one can find the dependence of the value of the gap $l$ on $R_e$ or $P_f$ for fixed values of the remaining parameters, which is of great interest in studying the problem of fitting thick-film resistive elements with a high-frequency flare discharge by a non-contact method.

The theory of the flare discharge is described in [13-24].

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