A CIRCUIT ANALYSIS APPROACH TO THE PERFORMANCE EVALUATION OF LASER-TRIMMED FILM RESISTORS

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Abstract. - Methods for predicting the performance of laser-trimmed film resistors are discussed. A figure of merit upon a sensitivity function, S^{HAZ}, is introduced which is useful for predicting aging and temperature performance of an arbitrary film resistor geometry with an arbitrary trim strategy. The proposed technique is incorporated in FIRE: a FORTRAN program for analysing arbitrary film structures with a given trim path. Examples illustrating the use of the suggested figure of merit are presented.

I. INTRODUCTION

Laser trimming of film resistors is an established process which allows manufacturers to very accurately control resistance values and resistor ratios.

When characterizing a trim structure, three important and inter-related points must be considered. Specifically, these are resistance determination, temperature effects and aging.

Trimmed film resistors (TFRs) show different performance than untrimmed resistors. In addition, the performance of TFRs is both trim path and geometry dependent [1]-[5]. It is desirable to keep the absolute and/or relative resistance changes due to aging and/or temperature variations as low as possible.

The laser trim causes heating and melting of the film material near the trim. This heating causes a change in the sheet resistance, the TCR and the aging characteristics in the zone adjacent to the trim, henceforth termed the Heat Affected Zone (HAZ).

A computer program for analyzing FIlm REsistors of arbitrary geometries and a position dependent sheet resistance is discussed.

A figure of merit, S^{HAZ}, is introduced which is useful for predicting temperature effects and aging characteristics of arbitrarily shaped laser-trimmed film resistors. Applications of the figure of merit are discussed.

II. HEAT AFFECTED ZONE EFFECTS

A laser beam is commonly used to trim film resistors. During the trimming process, a region along the edge of the resultant laser cut is nonuniformly heated to very high temperatures by the laser beam but the temperature rise is not enough to vaporize the material (see Fig. 1). After cooling, this "Heat Affected Zone" is characterized by physical properties which differ from the untrimmed portions of the resistor. Specifically, changes occur in the sheet resistance, temperature coefficient and aging behavior.

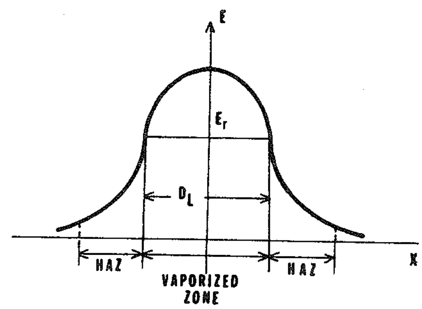

Figure 1. Spatial laser beam energy distribution.

In spite of the fact that the HAZ represents only a small fraction of the total film resistor area, its contribution to drift with time or temperature can be significant as will be shown in section IV. This is due to the fact that the total fraction of the power dissipated along certain portions of the HAZ can be very large. The characteristics of the HAZ thus are of concern in high precision applications.

III. EQUIVALENT CIRCUIT REPRESENTATION OF A FILM RESISTOR

Methods for solving the two-dimensional stationary field problem associated with the analysis of a film resistor are available [6]. One of these methods consists of subdividing the resistor structure into a large number of small equal sized squares. With this approach, a resistive circuit representation of the film resistor is obtained by replacing each square by the equivalent circuit shown in Fig. 2b. This analysis technique leads to an equivalent resistive circuit which contains a large number of nodes. For a fixed excitation, each nodal voltage approximately represents the potential at the corresponding position of each square. An iterative relaxation algorithm can be used to rapidly obtain the nodal voltage in the resistive network. Once the potential distribution of the TFR has been determined, the calculation of its overall resistance R can be easily acomplished by using the expression:

$$R = \frac{V_S}{I_S} \qquad (1)$$

where I_S is the current supplied by the fixed voltage source V_S (Fig. 2d).

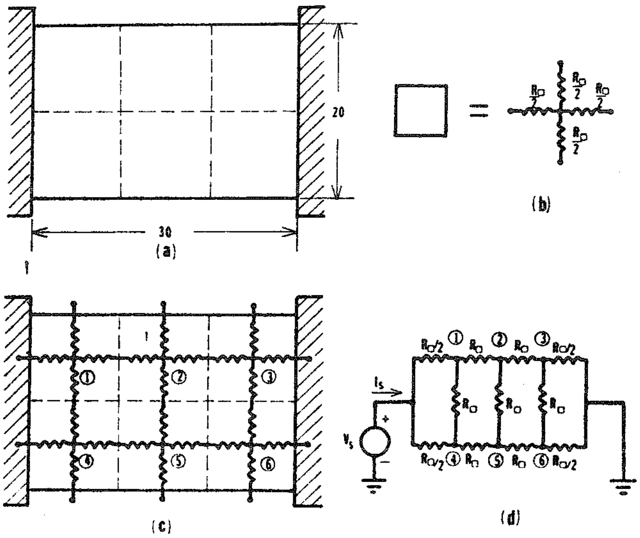

Figure 2. Derivation of an equivalent circuit for a homogeneous film resistor. (a) Homogeneous film resistor with aspect ratio 3:2 divided into 6 squares. (b) Equivalent circuit for a square element. (c) Circuit representation of a film resistor with 24 resistors. (d) Simplified circuit representation.

The program FIRE was written to find the nodal voltages at points inside the resistor. FIRE outputs the effective resistance R and gives plots showing the potential, current and power density distribution throughout the structure. FIRE is structured to allow user-enterable trim paths with user-enterable characterization of the HAZ surrounding the trim path. The program calculates a figure of merit which is useful for the evaluation and comparison of trimmed film structures.

IV. DERIVATION OF A FIGURE OF MERIT FOR FILM RESISTOR EVALUATION

In this section, figures of merit which are useful for predicting trimmed-film resistor performance in typical applications are presented. This figures are useful for comparing potential film resistor geometries and trimming algorithms.

A. Sensitivity of Resistive Networks to Individual Elements

The effects of a single resistor on the overall resistance of a resistance network are investigated in this section. Consider the totally resistive network NK excited at the input with a dc voltage source V_S as shown in Fig. 3. Assume that NK is comprised of N resistors. Create a second port by extending the two nodes adjacent to an arbitrary but fixed resistor, R_x. A sensitivity network is obtained by taking the partial derivative of the KCL equations characterizing NK with respect to R_x [7]. The sensitivity network is topologically identical to the original network, NK, with the exception that a current source shunts the single resistor R_x. If this current source is moved to the output port, the networks NK and $\widehat{NK}$ shown in Fig. 3a and 3c are topologically identical. The branch currents and voltages in the sensitivity network are related to the corresponding variables in the original network by the relationships

$$\widehat{I}_k = \frac{\partial I_k}{\partial R_x} \qquad (2)$$

$$\widehat{V}_k = \frac{\partial V_k}{\partial R_x} \qquad (3)$$

for $k = 1, ..., N$. The voltage source excitation on the input port of $\widehat{NK}$ is zero since $\frac{\partial V_s}{\partial R_x} = 0$.

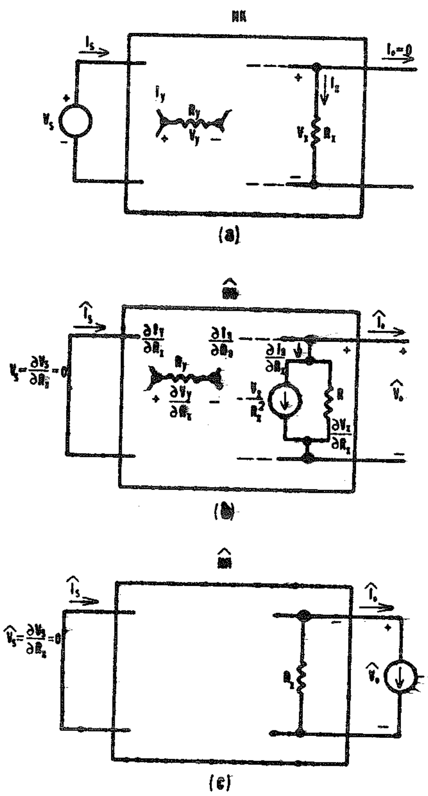

Figure 3. (a) Resistive network NK. (b) Sensitivity network $\widehat{NK}$. (c) Sensitivity network with $\frac{V_x}{R_x^2}$ moved to the output port.

Since networks NK and $\widehat{NK}$ and topologically identical, it follows from Tellegen's Theorem [8] that

$$\sum_{i=1}^{N} I_i\widehat{V}_i + \widehat{V}_s I_s + \widehat{V}_o I_o = 0 \qquad (4)$$

where I_i and $\widehat{V}_i$ denote the branch currents and branch voltages in NK and $\widehat{NK}$ respectively. Since $I_o = 0$ and $\widehat{V}_s = 0$, it follows that

$$\sum_{i=1}^{N} I_i \hat{V}_i = 0 \tag{5}$$

Consider now the input impedance to NK (treated as a 2-terminal network) which is, by definition,

$$R_{in} = \frac{V_s}{I_s} \tag{6}$$

The input power is given by the expression

$$P = \frac{V_s^2}{R_{in}} \tag{7}$$

By conservation of energy, this must equal the sum of the power dissipations in each of the resistors, hence

$$P = \sum_{k=1}^{N} P_k \tag{8}$$

where for all $k \epsilon (1, ..., N)$,

$$P_k = \frac{V_k^2}{R_k} \tag{9}$$

Define the sensitivity of R_{in} with respect to R_x by the standard expression

$$S_{R_x}^{R_{in}} = \left(\frac{\partial R_{in}}{\partial R_x}\right) \frac{R_x}{R_{in}} \tag{10}$$

From (6)-(10) it follows that

$$S_{R_x}^{R_{in}} = \frac{P_x}{P} - \frac{2R_x}{P} \sum_{i=1}^{N} \left(\frac{V_i}{R_i}\right) \left(\frac{\partial V_i}{\partial R_x}\right) \tag{11}$$

But, from (5) this last sum is zero, yielding the simple expression

$$S_{R_x}^{R_{in}} = \frac{P_x}{P} \tag{12}$$

It can be seen that the fractional power dissipation in any resistor (representing a local section of the film resistor) characterizes the relative affect of that resistor on the overall resistance.

This result is useful for the determination of trim resolution when designing trim algorithms. It can be concluded from (12) that removal of a small square element (forcing the sheet resistance of the element to go to ∞), i.e. trimming, results in an approximate percent change in R equal to the percent of the total power dissipated in the small element.

B. Effects of the HAZ on the Performance of Film Resistors

Consider now the more fundamental question which affects the performance of film resistors, specificially the change in a resistor R with respect to a parameter y such as temperature or aging. If we define a sensitivity function with respect to the parameter y by

$$S_y^R = \left(\frac{\partial R}{\partial y}\right) \frac{1}{R} \tag{13}$$

it follows that fractional changes in R due to changes in y can be approximated by

$$\frac{\triangle R}{R}\Big|_{y=y_o} \simeq (y - y_o)\, S_y^R\Big|_{y=y_o} \tag{14}$$

where y_o is the nominal value of y. Consider now the input impedance to the network NK of Fig. 3a. It follows that

$$\frac{\partial R_{in}}{\partial y} = \sum_{k=1}^{N} \frac{\partial R_{in}}{\partial R_k} \frac{\partial R_k}{\partial y} \tag{15}$$

From (10) and (12)

$$\frac{\partial R_{in}}{\partial R_k} = \frac{P_k}{P} \frac{R_{in}}{R_k} \tag{16}$$

Hence from (13), (15) and (16)

$$S_y^{R_{in}} = \frac{1}{P} \sum_{k=1}^{N} P_k S_y^{R_k} \tag{17}$$

This expression shows the contribution towards the total sensitivity of each element which comprises R_{in}.

The effects of a laser trim can now be characterized. Assume that after trim, the film resistor can be decomposed into a zone that was affected by heating, termed the HAZ, and a non-affected zone (the compliment of HAZ, $\overline{HAZ}$, in the geometrical sense relative to the trimmed resistor geometry). The sensitivity to HAZ is defined as

$$S_{HAZ,y}^{R_{in}} = \frac{1}{P} \sum_{R_k \epsilon HAZ} P_k \left(\frac{1}{R_\square(k)} \frac{\partial R_\square(k)}{\partial y}\right) \tag{18}$$

Although (18) is useful, in practical situations a significant simplification can be justified. In what follows, we will use a two-zone model to characterize a trimmed resistor. It will be assumed that the sheet resistance is characterized by $R_{\square 1}$ (film material outside HAZ) and $R_{\square 2}$ (film material inside HAZ). $R_{\square 1}$ $R_{\square 2}$and are assumed to characterize two geometrically homogeneous regions. $R_{\square 1}$ and $R_{\square 2}$ may, however, have different dependence upon the parameter y. With this simplification, the sensitivity in (18) simplifies to the readily calculable quantity

$$S_{HAZ}^{R_{in}} \simeq \left(\frac{1}{R_{\square 2}}\right) \frac{\partial R_{\square 2}}{\partial y} \left(\frac{1}{P} \sum_{R_k \epsilon HAZ} P_k\right) \tag{20}$$

We define the HAZ sensitivity, by

$$S^{HAZ} = \frac{1}{P} \sum_{R_k \epsilon HAZ} P_k \tag{21}$$

where P_k is the power dissipation of the resistor R_k. S^{HAZ} serves as a practical figure of merit for characterizing the effects of the HAZ. It is useful for comparing film geometries as well as trimming algorithms.

The total percent change in R_{in} can be readily obtained in terms of changes $R_{\square 1}$ and $R_{\square 2}$ If follows from (20) and (17) that

$$\frac{\triangle R_{in}}{R_{in}} \simeq \frac{1}{R_{\square 1}} \frac{\partial R_{\square 1}}{\partial y} (y - y_o)$$

$$+ S^{HAZ} \left[(y - y_o) \left(\frac{1}{R_{\square 2}} \frac{\partial R_{\square 2}}{\partial y} - \frac{1}{R_{\square 1}} \frac{\partial R_{\square 1}}{\partial y} \right) \right] \quad (22)$$

The two terms in in the right side of (22) have a straightforward physical interpretation: The first term $\frac{1}{R_{\square 1}} \frac{\partial R_{\square 1}}{\partial y} (y - y_o)$ represents a common change for all film resistors, trimmed or untrimmed, on a common film. The remaining term represents a trimm dependent change given by the heat affected zone sensitivity S^{HAZ} weighted by the technology dependent factor $(y - y_o) \left(\frac{1}{R_{\square 2}} \frac{\partial R_{\square 2}}{\partial y} - \frac{1}{R_{\square 1}} \frac{\partial R_{\square 1}}{\partial y} \right)$

V. Examples

To determine the relative significance of error associated with the HAZ, assume the variable y is temperature and that $T - T_o = 40^oC$. Assume $S^{HAZ} = 10\%$, and $\frac{1}{R_{\square 1}} \frac{\partial R_{\square 1}}{\partial T} = 100 ppm/^oC$, $\frac{1}{R_{\square 2}} \frac{\partial R_{\square 2}}{\partial T} = 200 ppm/^oC$. It follows from (22) that the trimmed resistor drifts 0.04% more than an untrimmed resistor. This becomes significant at the 11 bit level.

Of even more practical concern in many applications is the ratio matching accuracy maintainable over time and temperature with laser trimmed resistors. Consider two trimmed resistors RA and RB made of the same film material. Their ratio is r=RA/RB. Let S_A^{HAZ} and S_B^{HAZ} denote the fractional power dissipation (as defined by (21)) in HAZA and HAZB respectively. Assume the two resistors to be characterized by the two-zone model It can be shown that

$$\frac{\triangle r}{r} \simeq \left(S_A^{HAZ} - S_B^{HAZ} \right) \left[(y - y_o) \left(\frac{1}{R_{\square 2}} \frac{\partial R_{\square 2}}{\partial y} - \frac{1}{R_{\square 1}} \frac{\partial R_{\square 1}}{\partial y} \right) \right. \quad (23)$$

The designer has control of only the term $S_A^{HAZ} - S_B^{HAZ}$. This term can be minimized either by matching the two sensitivities or by making both simultaneously small.

Another example is very illustrative of the usefulnes of S^{HAZ} to determine optimal trimming strategies. Assume a ratio 1:1 is required. All resistors are nominal constant width bar resistors. The TCR of the HAZ will be assumed equal to $200 ppm/^oC$ and the TCR of the untrimmed film is assumed to be $100 ppm/^oC$. Two cases will be considered. In case 1, one resistor, R_{1A}, of dimensions $50\mu m \times 100\mu m$ will be fixed and a second, R_{1B}, L-trimmed to equal R_{1A}. The initial value of R_{1B} will be assumed to be $0.7R_{1A}$. R_{1B} is assumed intentionally undersized to allow for process variations. In case 2, it will be assumed that R_{2A} is $50\mu m \times 100\mu m$ and that R_{2B} is $50\mu m \times 105\mu m$ to account for a typical 5% mismatch due to processing. R_{2A} will be initially trimmed with a $25\mu m$ symmetric plunge and R_{2B} will be L-trimmed to match R_{2A}. A $5\mu m$ laser cut and a $2.5\mu m$ heat affected zone will be assumed. The geometric structures are depicted in Fig. 19. The sheet resistance in the HAZ is assumed to 75% of that in the untrimmed film and the TCR's of the untrimmed film and HAZ are assumed to be $100 ppm/^oC$ and $200 ppm/^oC$ respectively. The value of S^{HAZ} for the four resistors is shown in Fig. 4 along with $\frac{\triangle r}{r}$ as obtained from (23) for the case that Y is temperature with $y - y_o = 100^oC$.

The % error in the ratio in case 1 and case 2 corresponds to 10 bits and 14 bits respectively.

VI. CONCLUSIONS

A method of characterizing the performance of trimmed film resistors has been presented. A computer program which can analyze arbitrarily shaped film resistors with arbitrary sheet resistance has been introduced. A figure of merit, S^{HAZ}, which is useful for characterizing any trimmed film structure is readily calculated from the power density profile of a resistor.

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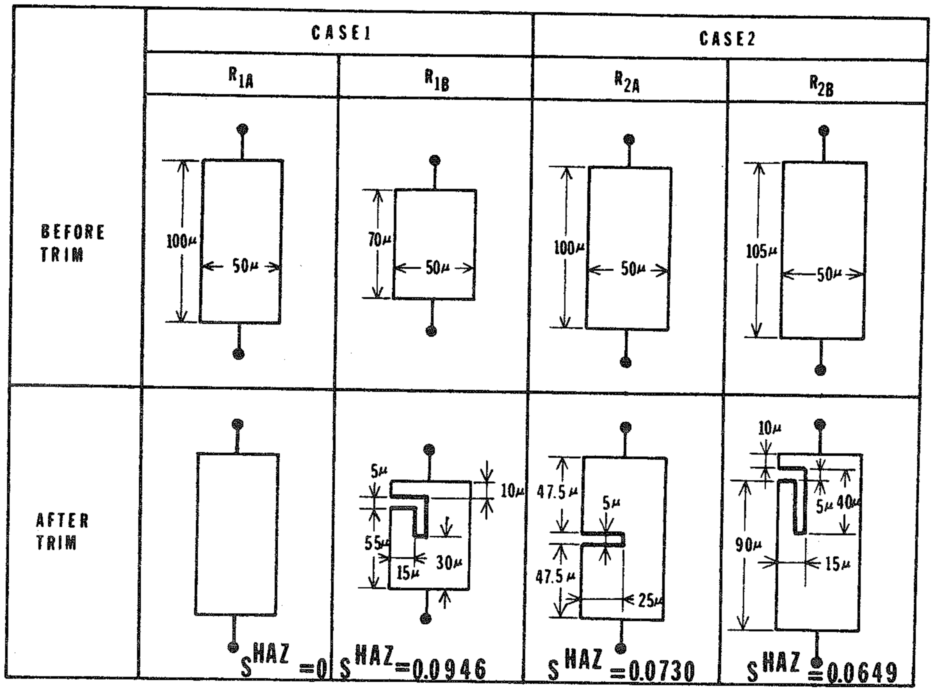

Figure 4. Ratio accuracy of trimmed film structures.

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