Downward Laser Trimming of Thick Film Resistors

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Abstract—**In this paper a method of laser trimming thick film resistors to lower resistance, that is downwards, is suggested. It involves heating of certain regions of the resistor film in the form of tracks (to a temperature where certain transformation in the structure of the film takes place, like segregation of the constituents of the resistor material, but not high enough to evaporate the material) by the use of a laser beam of appropriate power density. The heated regions are found to become regions of very high electrical conductivity. It has been found that trimming tracks made perpendicular to the current flow direction are not effective in reducing the resistance. On the other hand, trimming tracks made along the direction of the current flow are found to be effective in decreasing the value of the resistance. It has also been found that the resistance decreases with an increase in length and width of the track. This paper provides data from computer simulations and measurements made on analog resistor networks that enable one to design trimming tracks.**

I. Introduction

GENERALLY laser trimming is used to trim resistors upwards [1]–[4] by removing or cutting material in small areas, thereby reducing the flow cross section for current in certain regions. This method forces the designers of hybrid circuits to design resistors to lower values than they really need. On the other hand, if there is a method by which the trimming can be done upwards and downwards with the same tool, the designers can plan for the actual resistors they want and trim them marginally to take care of variations due to processing. Therefore, work was done on laser trimming to lower resistance. It has been possible to reduce the value of resistance by exposing the resistor film to a laser beam of such intensity that the material reaches a temperature where redistribution of its constituents can take place. What follows is a description of the downward trimming method and a discussion of work done to relate changes in resistance values to the dimensions and the location of the laser tracks.

II. Experimental Work

A. Fabrication of Resistors

Thick film resistors constructed from ruthenium-frit glass paste (Birox 1441 and 1451) and with Pd/Ag conducting paste (6130) for electrodes (both supplied by Dupont Japan Ltd) were screen printed on 96% alumina substrates and processed using standard thick film technique. Drying was carried out at 150°C for 15 min followed by firing in a three zone muffle furnace with the temperature of the central zone maintained at 850°C. The whole process of prefiring, firing, and cooling took a period of 1 h.

The processed resistors were trimmed downwards by exposing them to a continuous wave Argon ion laser with a maximum power output of 6.5 W and with a beam diameter of 1.5 mm. A lens was used to adjust the beam diameter.

B. Downward Trimming of Resistors

To trim a resistor, the output power of the laser was adjusted to 4 W and the resistor was moved with a constant speed of 4 mm/min in a direction perpendicular to the beam. Motion was along the length of the resistor; when the track was in the direction transverse to the current flow, it did not produce significant change in the value of the resistance. At this rate of movement and power density it was found that the material did not evaporate but its structure did change. When the exposed track extended from one electrode to the other electrode the resistance value was negligibly small compared to the original value. The results indicate that the laser treatment led to an increase in the conductivity of the exposed region. This formation of a high conductivity region is possibly due to the segregation of ruthenium oxide from the paste. (As the resistors are exposed to the laser beam, the frit glass melts first and ruthenium oxide being of different density from that of molten frit glass, it is expected to segregate, forming a continuous conducting layer in the exposed laser region.) A recent publication of Hofuku *et al.* [5] supports this hypothesis. Similar observations were also made on resistors fabricated with other Birox 1400 pastes such as 1411, 1431, and 1460. SEM photographs of the exposed resistors were taken to get an idea of the dimension of the tracks. A typical SEM photograph is shown in Fig. 1.

C. VCR Measurements

The voltage coefficient of resistance (VCR) for different trimmed and untrimmed resistors was measured according to the procedure given in MIL-STD-202F, method 309. Source measuring unit of Keithley make, model 236, was used for making these measurements. Table I gives the value of VCR for typical (trimmed and untrimmed) resistors. From the table it may be seen that the VCR for untrimmed resistors is in the range of -1.8×10^{-3} to -5.97×10^{-3}% and for the trimmed resistors it is in the range of -2.7×10^{-3} to -18×10^{-3}%. This indicates that the VCR has increased after laser trimming. Also one should note that the VCR is negative. It was pointed out earlier that due to the segregation

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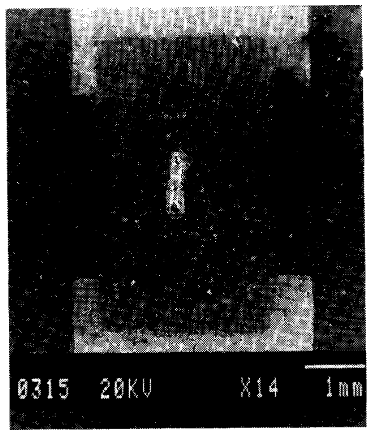

Fig. 1. Typical SEM photograph of the trimmed resistor.

TABLE I
VCR FOR TRIMMED AND UNTRIMMED RESISTORS

Trimmed Resistance in kΩ	VCR Percent	Untrimmed Resistance in kΩ	VCR Percent
2.6867	-9×10^{-3}	3.0464	-5.9×10^{-3}
3.3167	-13×10^{-3}	3.3714	-5.3×10^{-3}
4.6380	-2.7×10^{-3}	5.9185	-2.9×10^{-3}
6.1920	-18×10^{-3}	6.6521	-3.5×10^{-3}
9.7168	-8.41×10^{-3}	12.626	-3.5×10^{-3}
11.547	-6×10^{-3}	14.768	-3.4×10^{-3}
15.2745	-12×10^{-3}	18.356	-5.2×10^{-3}
34.275	-7×10^{-3}	44.312	-2.7×10^{-3}
90.456	-35×10^{-3}	119.232	-2.25×10^{-3}
154.559	-15×10^{-3}	169.491	-3.8×10^{-3}
177.808	-4.7×10^{-3}	178.794	-1.8×10^{-3}

of ruthenium oxide a conducting layer becomes formed which lowers the value of the resistance. One should realize that there is a high resistivity layer formed along with the conducting layer. These two layers are parallel to each other. The conduction through the high resistivity layer increases exponentially with voltage and, therefore, effectively lowering the resistance of the entire channel. This becomes reflected on negative VCR for the trimmed resistors.

D. TCR Measurements

Temperature coefficient of resistance (TCR) for different temperature ranges was determined following the method 304 suggested in MIL-STD-202F. The resistance was measured, at room temperature (26°C), 0, −15, and −55°C, and at 26, 50, 75, 100 and 125°C, using Fluke multimeter model 8842A. The low temperature was obtained using a cryostat model HC-2 supplied by APD Cryogenics. The high temperature was obtained using a temperature controlled furnace supplied by Toshniwal India Ltd. The TCR at each temperature was calculated using the procedure given in the above standard. These measurements were carried out on different values of resistors fabricated from different sheet resistivities. Table II(a) and (b) gives the percentage TCR for (untrimmed and trimmed) typical resistors. From these tables it may be seen that for untrimmed resistors the TCR is generally positive, except in some cases at low temperatures and for high

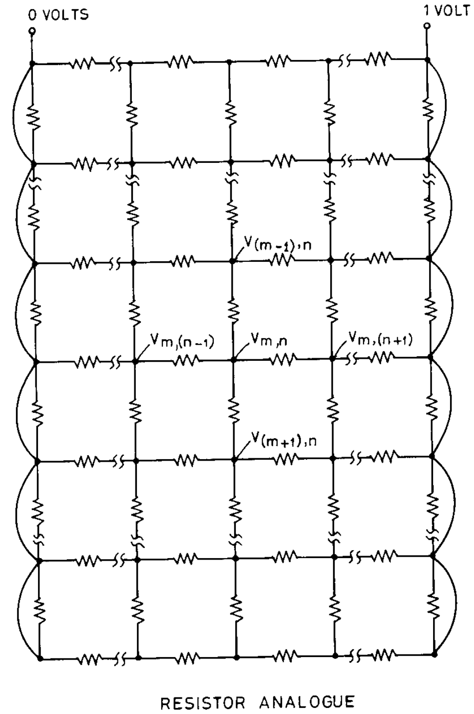

Fig. 2. Resistor analog.

value resistors. However, in the case of trimmed resistors, the TCR is generally negative for both small and large value resistors. This behavior can be understood on the same lines as given for the variation of VCR. As the temperature increases the conduction through the high resistivity layer increases rapidly, and as a result, the resistance of the trimmed track reduces, leading to a negative temperature coefficient in almost all the resistors at all temperatures. Even though the VCR and TCR values after laser trimming are slightly more than that of untrimmed resistors, these values seem to be well within tolerance limit, namely ±100 parts per million.

E. Resistor Analog

Thick film resistors were simulated on a resistor analog [6] consisting of discrete resistors of values of 3.3 kΩ which were connected in the form of a mesh as shown in Fig. 2. A trimmed resistor was simulated by forming the electrodes such that the number of rows was proportional to the width of the resistor and the number of columns was proportional to the length of the resistor. The trimmed portion of the resistor was simulated by shorting the appropriate columns and rows in the network with a view to verify the assumption that the trimmed region was of very high conductivity and could be represented by an equipotential surface. With the help of this analog, the ratios of the resistance values of the trimmed and the untrimmed simulated resistor were measured and compared with the corresponding ratios of fabricated resistors. Some of these are given in Table III(a) and (b). From the tables it may be seen that these ratios are very close to each other. This supports the assumption that the conductivity of

TABLE II
(a) TCR for Untrimmed Resistors. (b) TCR for Trimmed Resistors

Untrimmed Resistance in kΩ	TCR at 0°C	TCR at −15°C	TCR at −55°C	TCR at 50°C	TCR at 75°C	TCR at 100°C	TCR at 125°C
2.6321	6.3×10^{-3}	5.2×10^{-3}	2.8×10^{-3}	5×10^{-3}	7.5×10^{-3}	9.5×10^{-3}	10×10^{-3}
6.6351	1.4×10^{-3}	7×10^{-4}	-2.2×10^{-3}	3×10^{-3}	3.8×10^{-3}	5×10^{-3}	6×10^{-3}
7.6571	-2×10^{-3}	-2.7×10^{-3}	-6.5×10^{-3}	1×10^{-3}	1.9×10^{-3}	3.2×10^{-3}	4.4×10^{-3}
16.3251	6.1×10^{-3}	4.8×10^{-3}	2×10^{-3}	5.3×10^{-3}	6.9×10^{-3}	8.5×10^{-3}	9.4×10^{-3}
46.017	-2.1×10^{-3}	-4×10^{-3}	-7.6×10^{-3}	1.5×10^{-3}	2×10^{-3}	3×10^{-3}	4×10^{-3}
65.495	-4.9×10^{-3}	-5.6×10^{-3}	-9.7×10^{-3}	-5×10^{-3}	0	1×10^{-3}	2.4×10^{-3}
181.456	-5×10^{-3}	-6.4×10^{-3}	-11×10^{-3}	0	-2×10^{-3}	-2.2×10^{-3}	-1.5×10^{-3}

(a)

Trimmed Resistance in kΩ	TCR at 0°C	TCR at −15°C	TCR at −55°C	TCR at 50°C	TCR at 75°C	TCR at 100°C	TCR at 125°C
4.7080	2.8×10^{-3}	2.3×10^{-3}	3.8×10^{-3}	5×10^{-3}	3×10^{-3}	2.9×10^{-3}	3.8×10^{-3}
6.2026	-26×10^{-3}	-9.8×10^{-3}	-10×10^{-3}	3×10^{-3}	-6×10^{-3}	-5.6×10^{-3}	-3.8×10^{-3}
10.025	-12×10^{-3}	-9.6×10^{-3}	-10×10^{-3}	-9×10^{-3}	-6×10^{-3}	-5×10^{-3}	-9×10^{-3}
12.024	-8.6×10^{-3}	-10×10^{-3}	-10×10^{-3}	-18×10^{-3}	-10×10^{-3}	-9×10^{-3}	-6×10^{-3}
33.047	-9.8×10^{-3}	-12×10^{-3}	-14×10^{-3}	-23×10^{-3}	-16×10^{-3}	-14×10^{-3}	-15×10^{-3}
99.729	-1.7×10^{-3}	-3×10^{-3}	-7×10^{-3}	-2.6×10^{-3}	-2×10^{-3}	-8.5×10^{-3}	2.3×10^{-3}
179.822	-1.6×10^{-3}	-3×10^{-3}	-7.5×10^{-3}	-1×10^{-3}	-5×10^{-3}	3×10^{-4}	2×10^{-3}

(b)

TABLE III
(a) Variation of Resistance in Fabricated Resistors. (b) Variation of Resistance in Analog Simulation

Resistor number	Length of the resistor in micrometers L	Width of the resistor in micrometers W	Length of the laser exposure in micrometers l	Width of the laser exposure in micrometers w	$\frac{l}{L}$	$\frac{w}{W}$	Resistance before laser exposure R_0 in kΩ	Resistance after laser exposure R in kΩ	$\frac{R}{R_0}$
1	3850	3750	1190	132	0.309	0.035	12.61	12.07	0.957
2	2940	2650	785	200	0.266	0.075	110.7	102.8	0.928
3	2940	2650	880	248	0.299	0.093	99.9	92.8	0.928
4	2940	2650	922	237	0.313	0.089	118.5	105	0.886
5	2940	2650	1008	160	0.342	0.060	126.9	112	0.882
6	2940	2650	1557	186	0.529	0.070	110.3	86.3	0.786
7	2940	2650	2034	243	0.69	0.090	93.4	61.2	0.655

(a)

Resistor number	Length of the resistor network in simulation L	Width of the resistor network in simulation W	Length of the short in simulation l	Width of the short in simulation w	$\frac{l}{L}$	$\frac{w}{W}$	Resistance before making short R_0 in kΩ	Resistance after making short R in kΩ	$\frac{R}{R_0}$
1	28.74	28	8.88	0.98	0.308	0.035	3.61	3.29	0.911
2	31	28	8.2	2.1	0.264	0.075	3.84	3.51	0.919
3	31	28	9.26	2.6	0.298	0.092	3.84	3.4	0.885
4	31	28	10	3	0.322	0.107	3.84	3.29	0.856
5	31	28	10.6	1.68	0.341	0.06	3.84	3.26	0.846
6	31	28	17	2	0.548	0.07	3.84	2.69	0.700
7	31	28	22	3	0.69	0.1	3.84	2.16	0.570

(b)

the trimmed region is very high compared to that of the surrounding region. In general the ratios obtained through simulation are slightly lower than the ones that are obtained in the fabricated resistors. This deviation may be due to the fact that the trimmed region in the actual resistor does not have exactly zero resistivity, whereas in the simulated case it has exactly zero resistance. However, it may be noted that the deviation is small enough to validate the assumption that the trimmed region has nearly zero resistance. The variation of resistance with an increase in trim length, for constant trim width, and center location, was measured for different resistors. It was found that the resistance decreased with an increase in trim length. A typical variation of normalized resistance (normalized with respect to the original untrimmed resistor) versus trim length is shown in Fig. 3. Clearly, one can obtain considerable reduction in resistance by using the suggested trimming method. Further, it may be seen that one can use a resistor analog to design the trimmed region.

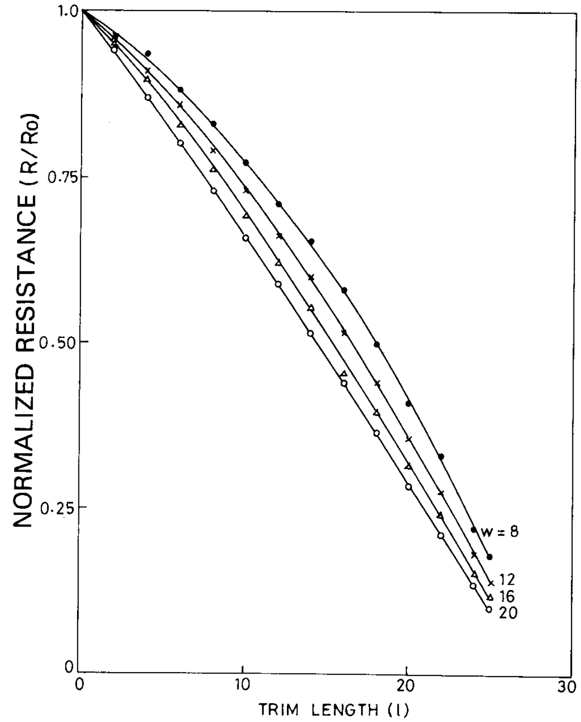

Fig. 3. Typical variation of normalized resistance versus trim length using resistor analog.

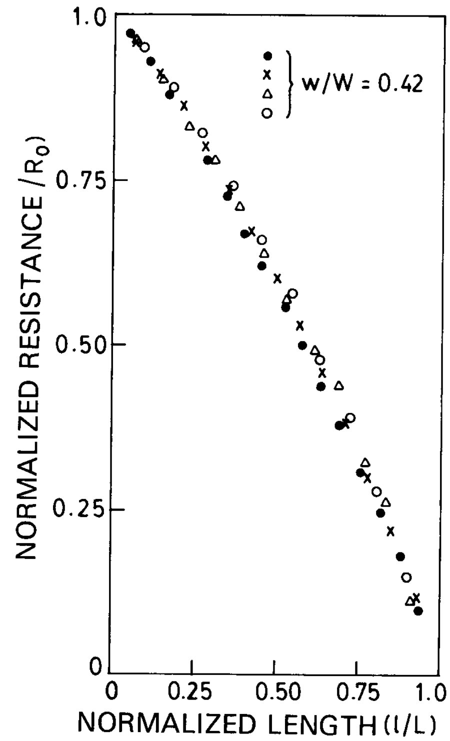

Fig. 4. Variation of normalized resistance with normalized length for different mesh lengths with constant w and W.

Because a resistance analog is not a common tool, a computer program was developed to calculate the resistance of a trimmed resistor through the solution of Laplace's equation.

F. Computer Simulation

The potential distribution in a resistor was calculated by finding the solution to Laplace's equation using a finite difference technique with an applied voltage of 1 V across the resistor. The current flowing through the resistor was then computed. The details of the program are given in the Appendix.

This program was used to calculate the ratio R/R_0, where R_0 is the untrimmed resistor value and R is the trimmed resistance value, for various sizes of resistors and trimmed regions. For four values of the lengths of the resistors, and for constant width of the resistor and of the track, the variation of R/R_0 was computed. The results are shown as a function of l/L, where l is the length of the trimmed region and L is the length of the resistor, see Fig. 4. It is seen that the ratio R/R_0 depends strongly on the ratio l/L. It was also found that R/R_0 depends strongly on the width of the track. The program was used to calculate the ratio R/R_0 for different l/L and w/W; the results are shown in Fig. 5. From the figure it may be seen that the maximum variation in the normalized resistance, when w/W is varied from 1 to 100%, is only about 0.2 (0.5–0.7) and it occurs for the value of $l/L = 0.5$. This result suggests trimming with larger track widths to avoid hot spots. It may be possible to carry out trimming with large track widths

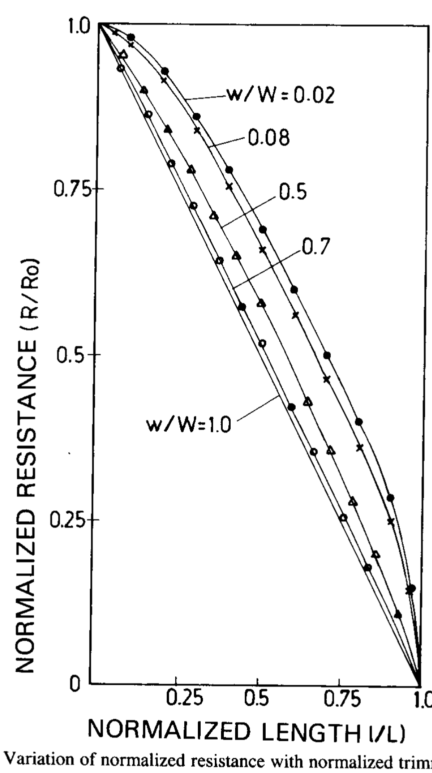

Fig. 5. Variation of normalized resistance with normalized trimmed length.

using the conventional laser trimmers as the power density needed for carrying out this trimming is low. The data given in Figs. 4 and 5 may be directly used for designing the central trimming region to effect any given decrease in resistance. For any other location of the trimming region or for any other l/L and w/W the method described in the Appendix has to be used to estimate the change in resistance that will occur.

III. Comparison of Downward and Upward Trimming

Unlike the case of upward trimming for which the material is evaporated from the trimmed region, in downward trimming the material remains in the same place, but is transformed. This process seems to be much cleaner than the one involved in upward trimming. Downward trimming needs lower power density than upward trimming, and therefore, with the same laser power one will be able to trim larger track widths in the downward direction.

When the resistors are trimmed only upwards the designers design the resistors to lower values than what are needed, sometimes as much as 20% lower than the actual values, and trim them upwards to account for the variations produced due to process uncertainties. If the process uncertainties produce say a change of ±15% the maximum change to be brought about due to trimming is 35%. On the other hand if both upward and downward trimming are carried out with the same laser equipment, the designers can design the resistors to the required value and trim them only to compensate for the variations due to process uncertainties, in this case the maximum trimming being 15% downwards or upwards. Thus it may be seen that the trimming effort becomes considerably reduced when upward and downward trimming are combined in the same laser trimmer. However, it may be noted that designing a laser trimmer which can cater to both downward and upward trimming might involve considerable effort.

IV. Conclusions

A method of trimming thick film resistors downwards by generating highly conducting regions in the resistor has been reported. It has been shown that this is possible using a relatively low energy density laser beam. It has also been shown that the trimmed regions can be designed using a resistor analog or a computer program given in this paper. Since higher power density laser beams are used for upward trimming, and as discussed in this paper, low power density beams enable downward trimming of resistors, future equipment may be designed to enable both upward and downward trimming with the same laser by changing the power densities.

Appendix

Details of Computer Calculation of Trimmed Resistors

Instead of measuring the potentials and the currents in a simulated resistor through resistor analog, they can be calculated using a computer. The following are some of the basic equations that may be used for the computation of the potentials, currents, and finally, the resistance of the network.

Since the sum of all the currents at any nodal point is zero, the potential $V_{(m,n)}$ at any nodal point (m, n) in the network is given by

$$V_{(m,n)} = 1/4[V_{m,n-1} + V_{m,n+1} + V_{m-1,n} + V_{m+1,n}] \quad (1)$$

where m is the row and n is the column corresponding to the node as shown in the Fig. 2.

The potentials at all the nodal points in the simulated resistor are calculated by using an iterative method in which an initial potential distribution is assumed for all the nodal points in view of the potential applied across the simulated resistor (to simplify the process a potential of 1 V is applied across the resistor). The potential at each nodal point is then updated using (1). However, at the boundaries of the resistor the equation is to be modified as:

$$V_{m,n} = 1/3[V_{m,n-1} + V_{m,n+1} + V_{m-1,n}] \quad (2)$$

where $m = 1$ represents one boundary and $m = M$ represents the other boundary of the resistor. For the trimmed region the potential is the same at all the nodes in it. The process of updating is repeated a number of times until the potential at any nodal point in the entire resistor does not change much between successive iterations. Using the potentials at various nodes in the first (electrode) and second column, the current flowing through the electrode is obtained as

$$I = \sum_{m=1}^{M} (V_{m,2} - V_{m,1})/r \quad (3)$$

where r is the value of the resistor connected between any two successive nodal points. If r is taken as 1 Ω and the electrode potential $V_{m,1} = 0$ for all m, (3) reduces to

$$I = \sum_{m=1}^{M} V_{m,2}.$$

The value of the resistance R of the simulated resistor in a network with $r = 1$ Ω is given by

$$R = V/I = \left(1 \bigg/ \sum_{m=1}^{M} V_{m,2}\right) \Omega.$$

To improve the accuracy of the calculation one may calculate the current flowing out of the other electrode and the average of these two currents taken as the current flowing through the resistor with 1 V applied across it. This leads to an expression for the resistance R, given by

$$R = \frac{2}{M - \left(\sum_{m=1}^{M} V_{m,(N-1)} - V_{m,2}\right)}.$$

Thus the value of the simulated resistance can be calculated with and without trimming, and hence, the percentage change due to trimming can be obtained.

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