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SIMULATION OF LASER TRIMMING OF FILM RESISTORS

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Abstract

Laser trimming is an indispensable step of manufacturing of high precision thick film resistors. In order to assure long term stability and reliability of laser trimmed film resistors, designers must prepare special trimming path regarding the real effects of laser cutting. The computer program created by the author, presented in this paper, is useful for analyzing influence of trimming an arbitrary film resistor with inhomogeneous conductivity by an arbitrary laser trim strategy, taking into consideration the effects of heat-affected zone (HAZ). Some real examples are presented to demonstrate the suggested use of this method, which helped the author to find such a complex cut line, which provides low current density, low noise, long term stability and reliability.

Keywords: laser trim, film resistor, Computer Aided Design (CAD).

Introduction

The accurate, stable, reliable film resistors are important components of modern electronic circuits. Since the tolerance of the resistance of thick-film resistors after screen-printing and firing are about ±20%, they need value corrections. Generally this step of manufacturing is done by computer controlled laser trimmer systems. By the help of the energy of laser beam the material of resistor is removed, thus the geometrical parameters of the resistor are changed, and the resistance is increased [1]. (If the laser beam heats the resistor film above the firing temperature, but does not remove material parts of it, the resistance can be decreased. This method is not wide-spread, because its result is not properly precise. The up-to-date commercial laser trimmer systems, depending on the accuracy of measurement and precision of beam positioning, can control nearly infinite resolution of resistance values. Thus the question is, why to use computer simulation, just measure and cut and it takes you to the right way.

The answer was given in the first rows in this chapter: the requirements of the resistors (the precise resistance, TCR, noise, etc.) should be fulfilled not only at the minute of trimming, but the good long-term and thermal stabilities are also very important. It is known from practice that the trimmed and untrimmed resistors behave differently after thermal and life time test.

The first reason is that in trimmed resistors the whole area of the film does not take part in current transfer, thus under the same working circumstances the current density is higher in the active part of trimmed resistors. The higher current density means higher density of power dissipation and higher temperature. Aging is a thermal activated process, so it runs more rapidly in the trimmed resistors than in the untrimmed ones. If the current induced temperature exceeds the firing temperature in the hot spot of the resistor film, the resistance decreases, making even higher current, so the resistance changes permanently until failure occurs.

The second failure mechanism is similar, but it originates from the laser beam, thus it is unavoidable. As it is shown in *Fig. 1*, in the edges of the laser kerf the material of resistor film was melted therefore its metallurgical and electrical parameters changed [2]. (It is termed the Heat-Affected Zone, HAZ). The effects of these zones cannot be measured exactly, because they are placed where the current density is higher and the measuring current causes an even higher change in the resistance. Other electrical parameters, such as TCR, noise, etc. are also changed in the HAZ.

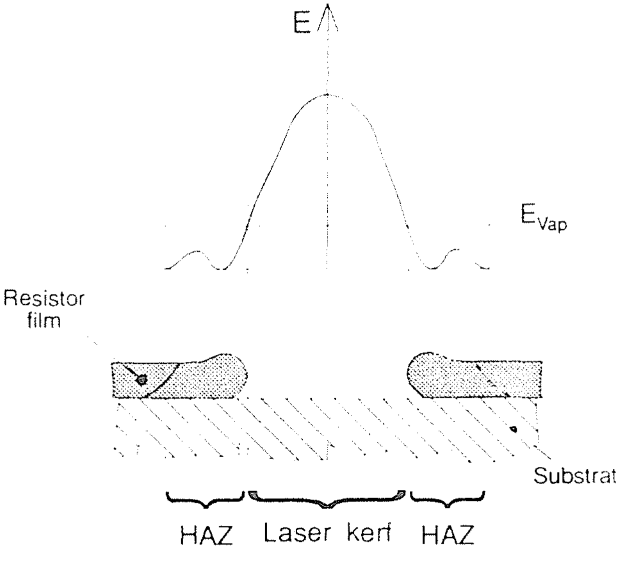


Fig. 1. The power distribution of the laser beam, E_{vap} is the vaporization threshold energy

The above mentioned problems show that in order to make laser trimmed film resistors with good reliability, the trim path should be chosen carefully to avoid the laser kerf induced current density growth. The trim path can be determined well only if the distribution of electric potential and current is known.

The Model of Film Resistors

The model of film resistors is based on the Maxwell's equations and it fulfils the boundary conditions given by the geometry of the film resistor and the equipotential contact layers. The parameters are assumed to be invariant in time, thus:

$$\text{rot } \mathbf{E}(\mathbf{r}) = -\partial \mathbf{B}(\mathbf{r})/\partial t = 0 \ . \tag{1}$$

The electric field, $\mathbf{E}(\mathbf{r})$ can be written as the gradient of a scalar potential function:

$$\mathbf{E}(\mathbf{r}) = -\text{grad } U(\mathbf{r}) \ . \tag{2}$$

According to Maxwell's 1st equation, the connection of the current density $\mathbf{J}(\mathbf{r})$ and the magnetic field $\mathbf{H}(\mathbf{r})$ is:

$$\text{rot } \mathbf{H}(\mathbf{r}) = \mathbf{J}(\mathbf{r}) \ . \tag{3}$$

Applying the operator of divergency on (3),

$$0 = \text{div rot } \mathbf{H}(\mathbf{r}) = \text{div } \mathbf{J}(\mathbf{r}),$$

so

$$\text{div } \mathbf{J}(\mathbf{r}) = 0 \ . \tag{4}$$

On the other hand, $\mathbf{J}(\mathbf{r})$ can be expressed by Ohm's law:

$$\mathbf{J}(\mathbf{r}) = \sigma(\mathbf{r}) \cdot \mathbf{E}(\mathbf{r}) \ , \tag{5}$$

where $\sigma(\mathbf{r})$ is the electric conductivity.

Substituting now (2) and (5) into (4),

$$\text{div } (\sigma(\mathbf{r}) \cdot \text{grad } U(\mathbf{r})) = 0 \ . \tag{6}$$

If $\sigma(\mathbf{r})$ is assumed to be constant, (6) will be the Laplace equation:

$$\triangle U(\mathbf{r}) = 0 \ , \tag{7}$$

else it will be the Poisson equation:

$$\sigma(\mathbf{r}) \cdot \Delta U(\mathbf{r}) + \nabla U(r) \cdot \nabla \sigma(\mathbf{r}) = 0 \ . \tag{8}$$

If one wants to know the value of $U(\mathbf{r})$ in any place of the resistor, he will have to solve (7) or (8) with the following boundary conditions (*Fig. 2*):

$$U(\mathbf{r}) = U_a \quad \text{if } \mathbf{r} \in L_1 \ , \tag{9}$$

$$U(\mathbf{r}) = U_b \quad \text{if } \mathbf{r} \in L_2 \ , \tag{10}$$

$$\mathbf{E} \cdot \mathbf{n}(\mathbf{r}) = 0 \quad \text{if } \mathbf{r} \in L_2, L_4 \ , \tag{11}$$

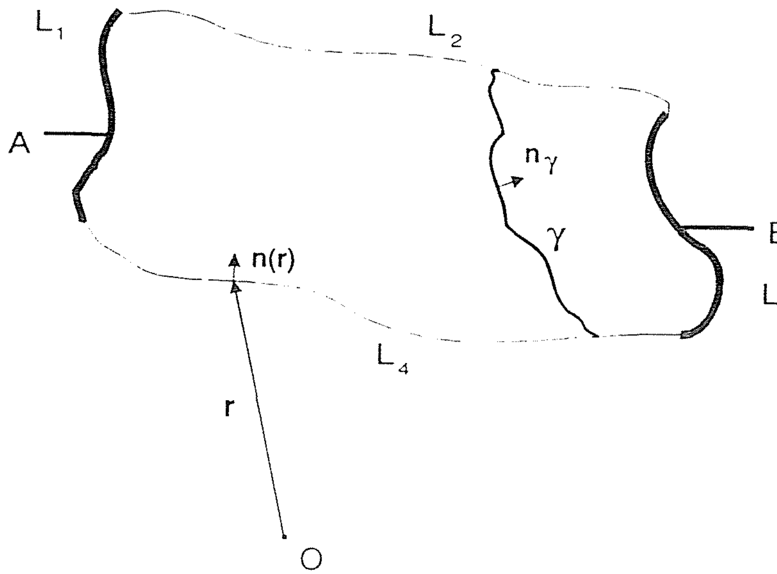


Fig. 2. An arbitrary film resistor

where L_2 and L_4 are the contact parts of the boundary of domain of resistor, L_1 and L_3 are the other parts of the boundary of resistor film, $\mathbf{n}(\mathbf{r})$ is the normal unit vector of the boundary in point P($\mathbf{r}$).

The equivalent resistance domain D is then

$$R = -\frac{U_b - U_a}{\int_\gamma \mathbf{J} \cdot \mathbf{n}_\gamma \cdot dl} \ , \tag{12}$$

where γ is an arbitrary continuous curve connecting L_2 and L_4, and $\mathbf{n}_\gamma$ is the normal unit vector of γ [3].

In order to determine the equivalent resistance domain, D, it is enough to find the distribution of current density along γ. Some other programs use semi analytical methods, like the Green's boundary formula [4] or extended Schwarz–Christoffel transformation [5] to find fast an approximate solution of (7). The author has chosen another way, because these methods do not provide the distribution of electric potential and current density on the whole region of the resistor film and they cannot handle inhomogeneous conductivity.

Our program uses the finite differences method to approximate the solution of (6). It lays two layers onto the domain of resistor, as it is shown in *Fig. 3.a*. Both layers are divided to cells by finite meshes. Each cell of the meshes can be imagined as a small square resistor with homogeneous conductivity. The conductivity of a resistor is derived from the approximation of the $\sigma(\mathbf{r})$ function. Each resistor connects ideal conductor bands, so in one layer the current flows only in the north-south and in the other layer the current flows only in the east-west direction. Between the two layers the connections are made by the crossing conducive bands (see *Fig. 3*).

This representation projects the domain of a film resistor into a resistor network (*Fig. 3.b*). The node voltages give the distribution of the potential along domain D. The value of the voltage in node (i, j) (in *Fig. 3.c*) can be calculated by successive over relaxation algorithm. At the $(n+1)$-th step of the iteration, the voltage is:

$$U_{i,j}^{n+1} = (1-\alpha)U_{i,j}^{n} + \frac{\alpha}{G}\Big[U_{i+1,j}^{n} g_{i,j}^{h} + U_{i,j+1}^{n} g_{i,j}^{v} + \\ + U_{i-1,j}^{n+1} g_{i-1,j}^{h} + U_{i,j-1}^{n+1} g_{i,j-1}^{v}\Big] \ , \tag{13}$$

where $G = g_{i,j}^{h} + g_{i,j}^{v} + g_{i-1,j}^{h} + g_{i,j-1}^{v}$, and $0 < \alpha < 2$ is the over relaxation coefficient. The superscript signs the serial number of the iteration in which the voltage gets a valid value, and the subscript signs the position.

Applying the above discussed model, an arbitrary inhomogeneous film resistor can be described by arbitrary accuracy, if the computer is fast enough.

This model is well suited for the simulation of laser cuts, because we should only replace zeros in the place of the conductivity of those small resistors which became insulating, and we can also change the value of the elements of the HAZ.

There is no need for the diameter and the step of the laser beam to be integer multiples of the step of the mesh, because the algorithm can be called recursively on those mesh elements which are only partly affected by the laser beam.

After the iteration the program immediately can report the distributions of the potential, the current density and the power dissipation.

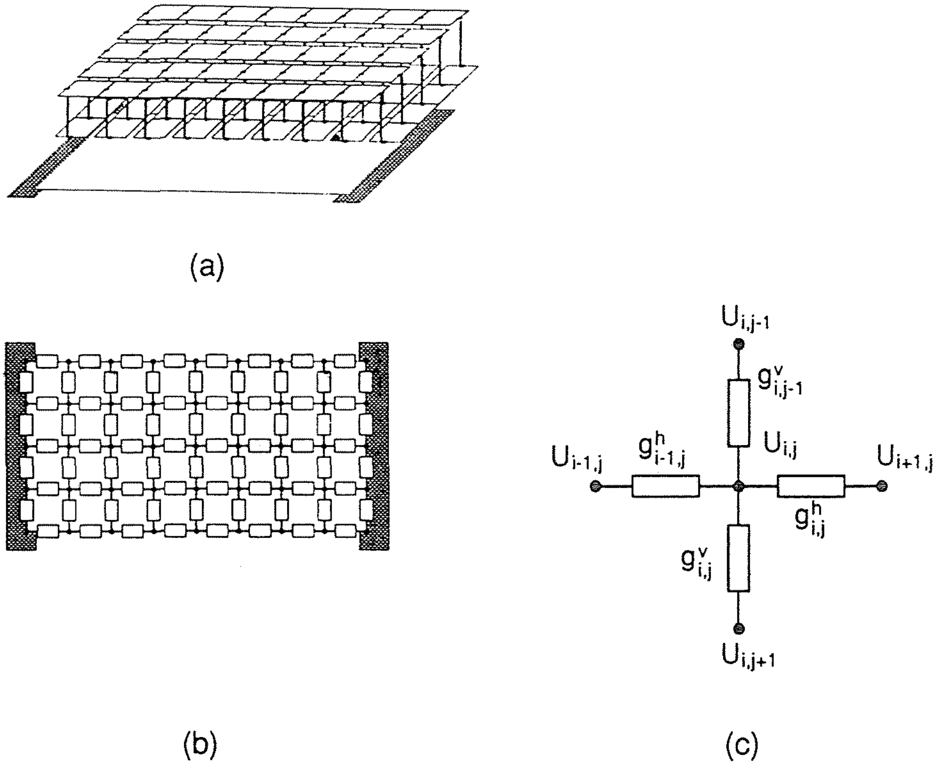


Fig. 3. The model of a film resistor

Examples

The examples presented in this section illustrate the effects of the different trimming cuts and set the trend in trim path design.

We have to design a simple rectangular resistor with the following parameters:

$$R_{\text{nominal}} = 25 \text{ k}\Omega \pm 1\% \,,$$
$$P_{\text{nominal}} = 250 \text{ mW} \,.$$

The space between contacts is:

$$L = 2500 \ \mu\text{m} \,.$$

We can use a usual resistor paste, with:

$$R_{\text{sheet}} = 10 \text{ k}\Omega \,,$$

and

$$P_{\max} = 200\ \mathrm{mW/mm^2}\ .$$

The tolerance of the technology is $\pm 20\%$ projected to R_{nominal}. The width of resistor W can be calculated by the worst-case design:

$$R_{\mathrm{sheet}} \cdot L/W = 0.8 \cdot R_{\mathrm{nominal}}\ ,$$

from where we get:

$$W = 1250\ \mu\mathrm{m}\ .$$

Checking the power dissipation,

$$P = L \cdot W \cdot P_{\max} = 625\ \mathrm{mW}\ ,$$

it is twice and half times more than the nominal.

After manufacturing we find the resistors in a resistance range with the lower limit of about $R_{\mathrm{sheet}} \cdot L/W - 0.2 \cdot R_{\mathrm{nominal}}$, , which is 15 k$\Omega$ in our case. It is the initial value of the resistors.

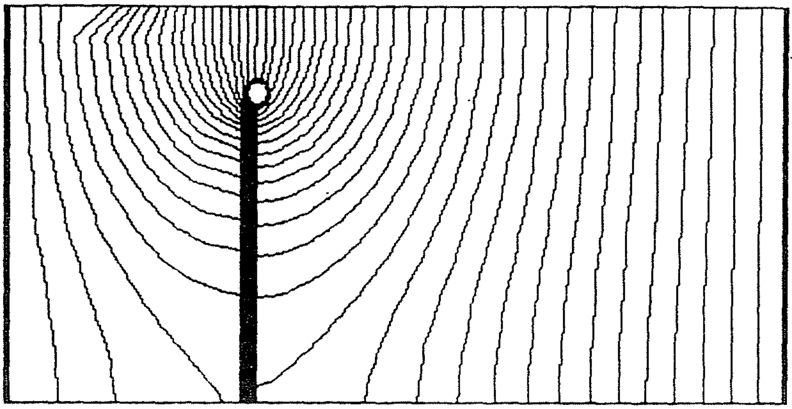
The laser trimmer system is available for the usual trimming routes, such as plunge cut, multiplunge cut and L cut. The diameter of the laser beam is 50 μm, and we use this spot size as the resolution for the simulation, thus the domain of resistor is divided into $25 \cdot 50 = 1250$ squares.

As the result of the simulation we present some figures, which show the place of the laser cut and the equipotential curves. The circle shows the place of the maximum power density. The values of the maximum current density and power dissipation are relative to the value which we would receive, if the resistance of this geometry were equal to R_{nominal}(25 kΩ). If the power dissipation is higher than 2.5, it oversteps the limit of the paste.

The disastrous result of the simulation of a single plunge cut is shown in *Fig. 4*. The distance between the kerf and the nearer contact is 750 μm, the length of the trim path is 76% of the resistor width. The circle shows the place of the maximum power density at the end of the cut, its value is 16.232, which is far over of the viable limit of the resistor material. We cannot predict a long life time for this device.

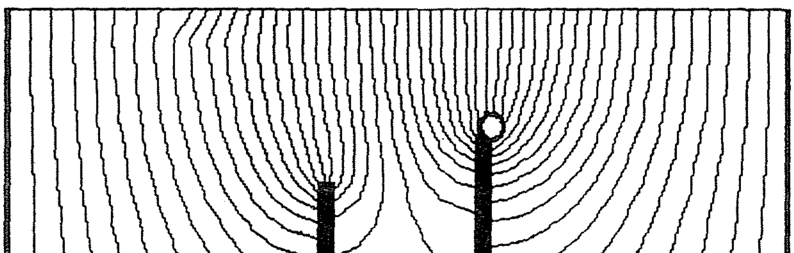
Using twin plunge cut (*Fig. 5*), the peak of the power dissipation can be reduced, but it is still four times higher than the admissible limit. The trajectories of potentials are strongly curved and the bottleneck of the current conductive cross-section is only 32% of the width.

The well known L cut (*Fig. 6*) can smooth the equipotential curves down in a long part of the resistor, and the dissipation decreases below the critical value, but the end of the kerf does not show high confidence. If we consider the HAZ along the long kerf, a wavering stability can be predicted.



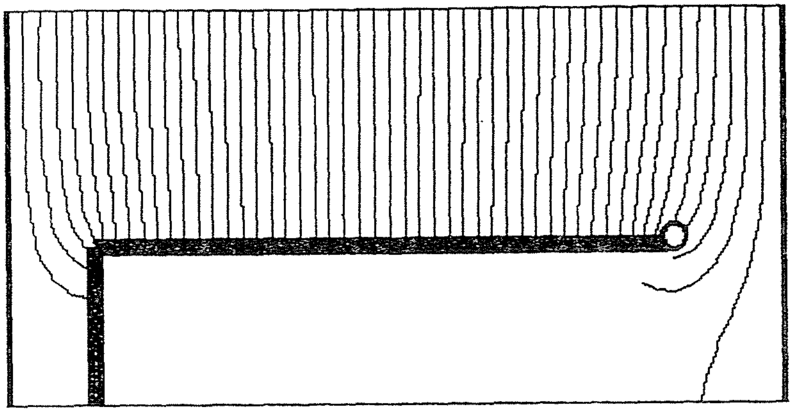
Resistance : 24984 Omh
Maximum current density : 5.118 units
Maximum power dissipation : 16.232 units

Fig. 4. Program report of plunge cut



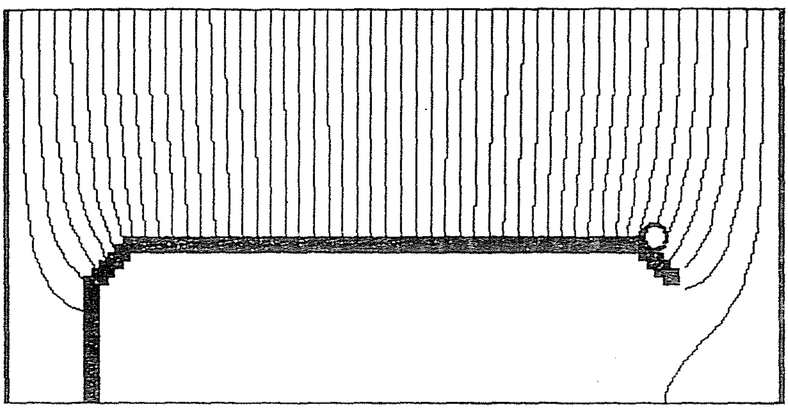
Resistance : 25237 Omh
Maximum current density : 4.233 units
Maximum power dissipation : 10.927 units

Fig. 5. Program report of twin plunge cut



Resistance : 24815 Omh
Maximum current density : 1.975 units
Maximum power dissipation : 2.106 units

Fig. 6. Program report of L cut



Resistance : 24789 Omh
Maximum current density : 1.701 units
Maximum power dissipation : 1.577 units

Fig. 7. Program report of modified L cut

Close to the long kerf the current density is higher than in the other parts of the resistor, so the noise will increase.

The last type of trimming strategy (*Fig. 7*) was developed to solve this problem. The trim path can be divided into four parts. The first is a plunge cut, but it is shorter than the first part of a conventional L cut. The second part is a straight path with a 45 degree slope, whose length is only a few steps of the laser beam. Its role is to eliminate the dense current lines which can be found at the break point of the L cuts. The third part is the same as the X-direction path of L cuts, but it ends a few tenth per cent earlier. The last 45 degree kerf can give higher precision and it drives the current lines into softer ways. The value of the maximum power dissipation is 25% lower than the value of the L cut, it is only 1.577. The length of the kerf is nearly the same, but the current density close to the cut is lower, thus the changes of the parameters in the HAZ are hoped to be lower than those of the L cuts.

Conclusion

A new method for the simulation of laser trimming of film resistors has been presented. The model and the algorithm have been coded in C programing language under MS DOS on AT 386. The potential, power and current density profiles of a user defined arbitrary geometry can be drawn, and inhomogeneous conductivity can be taken into consideration.

The performance of several trimming paths has been analyzed and the optimum algorithm has been determined.

The program is under development, and in the near future it will handle an accurate, place dependent conductivity distribution model including automatic HAZ generation.

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