Film Resistor Design for High Precision Laser Trimming

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Abstract

Nowadays with powerful computing techniques is it possible to step away from resistance approximations and use fast differential equation solving techniques which adequately describe the current flow through a thin film resistor. The trim characteristic and the final trim resolution can be calculated with extreme accuracy. This improves the resistor design process itself, allowing resistors with the desired range and resolution to be optimized quickly for the minimum real estate occupation. This paper shows how it is possible to design systematical trim strategies by using of numerical trim simulations in the resistor design process and how it can predict and improve the trim results in monolithic circuit manufacture.

Introduction

The functionality, capability and reliability of modern hybrid IC's depends on precise resistor values and tolerances. In practice, however, high precision resistors are difficult to manufacture. Process variations, as well as the natural distribution and drift of thin film resistors within circuits are responsible for this. Functional laser trimming at the wafer level has become the most popular method of individually tailoring each die on a silicon wafer to meet precise resistor specifications.

Because of the high cost involved in adding laser trimming to the manufacturing steps it is highly desirable to optimize the size, shape and trim pathway of resistors to be trimmed. Optimized size for a given range and resolution minimizes chip real estate usage and optimized trim pathways result in high-speed laser trims. This optimization process starts at the design stage and ends at the final multiprobe stage where trimming takes place.

It is possible to mathematically describe how a resistor changes as a function of geometry and trim pathway. Unfortunately the reverse of this process, to generate a resistor design geometry from a desired target resistance and trim resolution, is presently not possible analytically. This means the only way to design a resistor that will meet the specifications is to make a first guess at the geometry, execute a trim and then check if this conforms to the desired range and resolution. This process then goes through several iterations until a suitable resistor design is reached. Briefly, simulation experiments are required and there are two ways to achieve this. The first one is to build a physical model. The most reliable way is to produce a prototype in the specific technology, but also macroscopic equivalence models with resistor paper or electrolytical pools for instance are used ways for that (/11/, /12/). This method is expensive, time consuming and has low flexibility, especially if several iterations are required, although it does produce accurate results. The second method is to create a mathematical model and to perform the experiments with a computer simulation. This is considerably more practical and much less time consuming, however the accuracy of such numerical simulations depends on the exactness of the mathematical model employed.

In the past several different mathematical models and approaches have been used to simulate resistor trimming. These approaches have ranged from using approximations and extrapolations from measured real world data, to the division of the resistor domain into simpler regions. The latter technique is known as the 'Square Count Method' where the resistance is estimated for certain regions and the re-composition of these regions gives the resistance of the whole domain (/10/).

A much more rigorous and exact mathematical model would be to solve the dedicated partial differential equations (PDE), the Laplacian-Equation derivated from Maxwell's Equations, with the appropriate boundary conditions for stationary voltage potential field φ in the resistor domain. The resistance of that domain can be calculated by the equation of the so called spread resistance, which is only another formulation of Ohms law (/13/):

$$R_{ab} = \frac{\int_{ab} \nabla\varphi \, d\vec{s}}{\iint_A \kappa \nabla\varphi \, d\vec{A}} \text{ , where } div(\kappa\nabla\varphi) = 0 \text{ with boundary conditions}$$

(κ: material's conductivity; *s*: path length of the current lines; *A*: area where the entire current flows through)

However, this PDE is in most geometrical cases not explicitly solvable and it is necessary to use numerical methods.

To date the most popular rigorous mathematical model for resistor calculations has been the Finite Difference Method (FDM). However, a high number of FDM cells are necessary for sufficiently accurate results, especially for frequently used non-convex resistor geometries. But a higher number of cells decreases the calculation speed dramatically with computation times becoming impracticably long for any reasonable accuracy. One advantage of the FDM is that this method can simply be used on a spread sheet program which is able to make iterative calculations. On the other hand the handling of such a program is cumbersome (/8/).

Another approach for example is to solve the PDE with the Finite-Element-Method (FEM). This method is much more flexible to adopt non-rectangular domains, because a non-rectangular, not axis-parallel mesh can be used to discretisize the domain. Unfortunate, to generate such kind of mesh an higher effort and several refinement iterations with mesh smoothing, re-computation and error estimation for each element of the potential field, φ is necessary (/7/, /8/, /9/). But exactly this is one of the reasons why the FEM produce usually much more accurate results than the FDM (/8/). However, in /8/ is shown that the FDM is only a special case of the FEM appraoch without the capability of its flexibility because the need of axis-parallel, recktangular elements.

A more suited method to compute the resistance of an arbitrary resistor shape is the Boundary Element Method (BEM). In contrast to the FEM the BEM uses a contour discretizaton of the domain only. That means for film resistor calculations is it an one-dimensional discretization problem instead the two-dimensional one for the FEM/FDM. This fact alone saves a lot of computation time. In addition the BEM forces the residuum (distributed error) on the boundary to a minimum. The FEM don't do that, this one minimizes the residuum only inside of the domain (/8/). But for resistor calculation the current flow across the connector boundaries is of interest to compute the spread resistance formula and not the potential field inside the domain. The absolute current flow difference between both connectors can give a global error indication, f_g of numerical resistance results. Figure 1, for

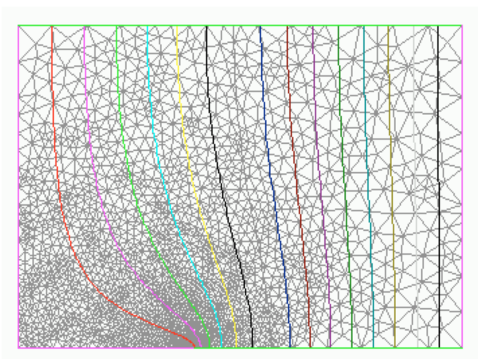

Fig. 1 FEM solution of a 3-side bar resistor

example, shows a FEM-discretization of a rectangular resistor with 6,085 linear approximating triangular elements after 16 refinement cycles. One connector is right hand side and the other one left hand side and a part of it at the bottom line, what creates a worse singularity at its end. The measured resistance was R= 1.185 ±0.001 kΩ. The nominal FE-result was 1.215 kΩ by $f_g = 8.15 \cdot 10^{-3}$ kΩ and it took 202 seconds to compute (including all 16 mesh refine steps). The same shape calculated by the BEM with 288 equidistant, constant approximating boundary elements result in nominal 1.213 kΩ by $f_g = 1.3 \cdot 10^{-5}$ kΩ and it took only 21.4 seconds (result without using a mesh refinement) on the same hardware (Pentium 200MHz). The homogeneous case of a bar resistor is the one and only where the FEM is faster than the BEM used here, because of BEM's lower (constant) degree of approximation and because the linear FEM-elements don't need to be local refined in this particular case. But each cut path produces an inhomogeneous flux field. Note, that for each laser cut step the PDE needs to be solved once and that it is impossible to create a proper a priori FEM mesh. The nominal resistance deviation is a generally observed phenomenon. The reasons are sheet resistivity variations, as well as unknown contact resistances, as well as geometrical deviations, as well as the 2-dimensional model simplification. But all these are systematic error influences who can be minimized by using of relative values. Figure 2 shows a BEM-model computed, relative trim characteristic (see below) in comparison with 3 measured data rows of the same top-hat shape with the same side cut. The entire characteristic was computed with a lower precision than above in 16 minutes on a Pentium 200 MHz and the PDE was solved 121 times at run time.
The reader may be refered to /1/-/6/, /8/ for further details on BEM.

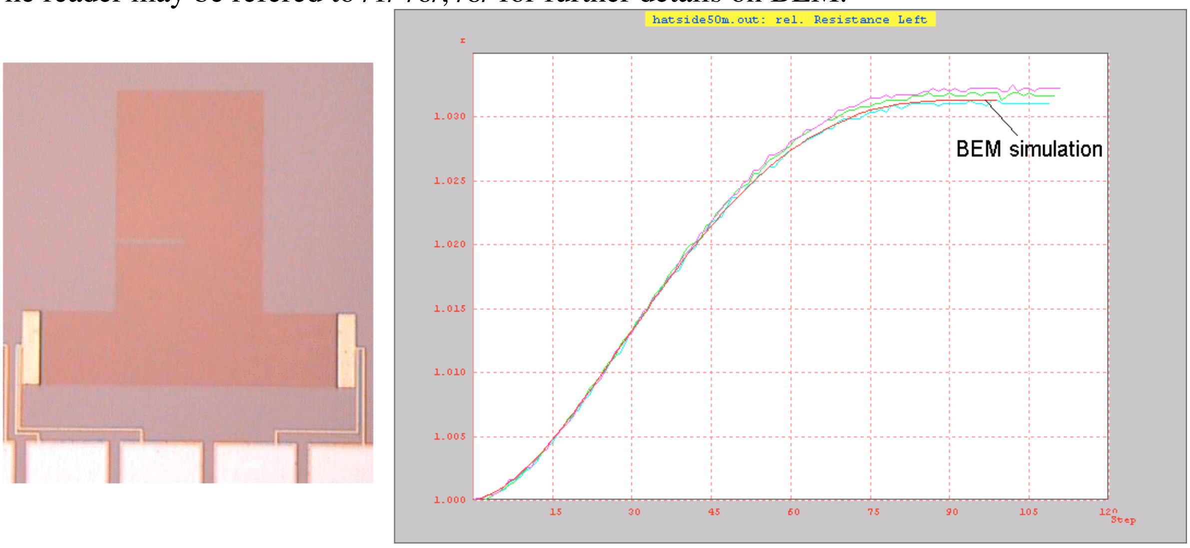

Fig. 2 Three measured trim characteristics of the same top-hat side-cut in comparison to the numerical result

The use of the BEM results in a more flexible trim simulator package that is capable of combining both speed and accuracy. This means that different resistor geometries and trim pathways can be quickly optimized, making the thin film resistor design stage much more predictable. Since optimized resistors and trim strategies enhance both design and production efficiency, such a simulation package can result in considerable cost savings.
Now the paper will discuss and demonstrate a method how a numerical simulator of this kind can be used for design of precise film resistors and the associated trim strategies, independent which concrete numeric is involved.

Preparations and Assumptions for Resistor Design

For a proper layout, both electrical and process specifications are needed. The electrical parameters are the target resistance R_t, the target tolerance or, for matched pairs, the half target resolution ΔR_t and finally the maximum current I_{max} through the resistor. The process parameters are the sheet resistance of the material, R_S and the symmetrical process tolerance, ΔR_S. Other essential parameters are the available die area *A*, the laser step size or bite size *W*, the trim kerf width *K* and the maximum allowable current density J_{max} of the resistor material. The current density *J* has the unit A/m, because it is multiplied by the constant film thickness. The minimum kerf width is limited by the minimum laser spot diameter.

Parameter	Unit	Name	Description
R_t	Ω	Target resistance	Final desired value of the circuit resistor after trimming
$\pm\Delta R_t$	Ω	Target resistance tolerance	Maximum allowed nominal variation from the target resistance for a proper circuit function
I_{max}	A	Maximum current	Maximum possible current flow through the circuit resistor
R_S	Ω/sq	Sheet resistance	Nominal resistance of a film material quadrate (sq= square)
$\pm\Delta R_S$	Ω/sq	Sheet resistance tolerance	Maximum process variation of the sheet resistance
J_{max}	A/m	Maximum current density	Maximum current density the film material can withstand without permanent damages (multiplied by the film thickness)
A	μm^2	Real estate	Maximum available area for the resistor shape (as enclosing rectangle)
W	μm	Bite or Step size	Minimum feasible laser spot movement between two laser bites
K	μm	Kerf width	Cut diameter of laser spot
R	Ω	Trim range	Minimum resistance **interval** that the trim strategy has to cover
J_{sim}	A/m	Current density result	Computed current density (multiplied by the film thickness)
λ_a	-	Resolution stretch factor	Minimum shape stretch factor to achieve the desired trim resolution
λ_b	-	Current density stretch factor	Minimum shape stretch factor to achieve the desired power level specification
λ_c	-	Geometrical stretch factor	Minimum shape stretch factor to ensure the technical feasibility
λ	-	Shape stretch factor	Minimum general shape stretch factor
s_t	-	Target trim sensitivity	Maximum relative trim sensitivity per step that meets the desired target tolerance (for absolute trims) or trim resolution (for pair matching)
s_{sim}	-	Maximum trim sensitivity of a cut path	Maximum of a relative trim sensitivity curve of a single cut path
W_{sim}	μm	Simulation bite size	Bite size who is used for the simulation
A_R	μm^2	trimmed area	Identifer for the minimum remaining resistor area in the case R_t is reached by the trim strategy
L	μm	Outline length	Length of the shape enclosing rectangle
H	μm	Outline height	Height of the shape enclosing rectangle

Table 1 Parameters involved in designing resistors optimized for laser trimming.

First of all, the necessary minimum trim range, R is to know for an appropriate resistor shape creation. The trim range must be large enough that the resistor can always be trimmed to its specified target resistance R_t even in the worst possible processing conditions of high or low sheet resistance expressed by $R_S \pm \Delta R_S$. Note that the trim range R is independent from the target tolerance ΔR_t. The trim range can be calculated by the following equation after a sheet resistivity R_S and its tolerance ΔR_S is specified:

$$\Delta R = R_s R_t \left[\frac{1}{R_s + |\Delta R_s|}, \frac{1}{R_s - |\Delta R_s|} \right] \qquad (1)$$

In the special case of resistor pair matching usually the variation of the sheet resistance between each untrimmed pair member is very small. This is because the two resistors are generally located close to each other on the die, where the sheet resistance is similar. However, the maximum sheet resistance change per unit distance is usually unknown and cannot be used as a parameter.

One important component that drives the final resistor area is the specified trim range. A larger trim range usually results in higher occupation of die real estate. This means that the wider the sheet resistance tolerance, ΔR_S that the process can provide, the more space that the resistor design will ultimately occupy on the die.

Since it is only possible to increase a resistor value by trimming, it follows that the design of the initial (untrimmed) resistor should correspond to the *highest* sheet resistance limit provided by $R_S + \Delta R_S$. Conversely, the designed trim range should, of course, be large enough that there is room to trim to specification even in the case that the *lowest* sheet resistance is present. In the frequently used case of pair matching, however, this rule can sometimes be relaxed. If the sheet resistance variation across the wafer is smaller than the absolute resistor values that will achieve adequate circuit performance it is beneficial to choose the target resistance R_t for the initial design. In this case there is nothing to be gained from using the lowest sheet resistance as this will only entail providing more trim range and thus using more valuable real estate.

Another important set of distinctions that needs to be considered is the difference between *finite* and *infinite* cuts. Although one may at first think that the upper limit of R is not relevant in the case of infinite cuts, it is important to realize that this is not true for high precision trims. An *infinite cut* is defined as a cut that eventually produces an infinite resistance, for example a plunge cut into a bar resistor. A *finite cut*, on the other hand, terminates with a finite resistance value, such as a side cut in a top hat resistor, or almost any inner cut. Also can be defined a *cut path* as a single straight line cut, and a *trim path* as a laser trim that consists of more than one cut path. Furthermore, if a trim path contains a finite cut as its final component then it is referred to as a *finite trim path*, e.g. an L-cut. When all cut paths of a trim cut are infinite this is referred to as *absolute infinite* and a trim path is *absolute finite* when all cut paths are finite. For example a serpentine trim path of a bar resistor is absolute infinite and a stairway side cut in the upward direction of a top hat resistor is absolute finite.

Absolute finite trim paths cannot exceed a certain upper resistance. Thus the upper limit of R is to use for layout a proper resistor pattern. Furthermore, such trim paths always have a finite trim sensitivity. Finite trim paths containing at least one infinite cut can of course end up with a infinite resistance and sensitivity. Since the initial resistance can have the upper trim range itself as the worst case, technological parameters at this point are to consider too.

All of the above is also true for infinite trim paths. Cut paths that end up with an infinite resistance will always violate the trim sensitivity limit. Such designs are less suitable for high precision trimming, unless a second qualified cut is used to reach the final resistance with the required tolerance and resolution. Examples of this are a plunge cut followed by a shadow cut, or an L-cut in bar resistors. However, during the laser trimming process it is hard to predict when the first cut should be terminated and at which location the second cut should to be started. Sometimes trim strategies like plunge cuts with a shadow are unavoidable, especially if there is a premium on available chip real estate. To guarantee success a mathematical simulation employed in the design stage is highly recommended.

Laser trims that contain *multiple trim paths* are more complex, because of the existence of turn and restart points which have to be predicted during the trim process itself. The trim characteristic of any given path then depends on its predecessor, leading to an infinite number of possibilities. For a precise treatment of multiple trim paths a multidimensional set of trim characteristic curves is often necessary. Such sets can be generated from a range of simulation cycles. In general it is recommended that trims such as these should only be chosen if absolutely essential. Again an exception to this rule is the bar resistor L-cut, because existing Square Count Models are precise enough for simulations. Even for the simple L-cut some different turn point conditions can be applied. For example, the stop condition for the first plunge cut may be a certain given resistance, a certain location, or in some cases the point where the second cut becomes a maximum length to create a low noise resistor.

Resistor Layout and Trim Strategy

The first step in designing a resistor layout is deciding on the optimum resistor shape or geometry. The chosen geometry essentially defines the trim strategy that will be used. In addition to the well-known resistor shapes (top hats, etc.), with the numerical simulator described here it is possible to create almost any shape imaginable that will fulfill the requirements. Because of the independence of the resistance with the resistor size, it is only the resistor edge aspect ratio that is initially important and not its absolute dimensions. The absolute dimensions will become important only when a practical trim is considered, since the minimum laser spot size eventually determines the smallest bite size and the maximum resolution. In the first step the only thing to consider is creating a resistor shape that has the resistance of the lower limit of R for the average R_S.

The number of possibilities is, of course, infinite and performing this step requires a certain amount of experience. A flexible shape editor that can also quickly estimate resistance is invaluable in rapidly finding a set of useable shapes, even though this is still a trial and error process. During this search process the designer needs to keep in mind that the resistor will be trimmed eventually, and so a few trim path ideas should already belong to each sample. At this early stage is it wise to check the trim range of the trim paths in mind by temporarily changing the resistor shape to a new shape that is equivalent to the maximum trim geometry. This is very easy for absolute finite trim paths, because of the existence of natural boundaries. For infinite cut paths, however, virtual limits for the cut path lengths are to create and to justify. These limits should be guided by a set of rules. Such a rule, for example, is that a plunge cut into a bar resistor should not go deeper than 50% of the bar width. For multiple trim paths additional restrictions can be necessary. For example the maximum parallel distance of a shadow cut path to the first plunge cut and its maximum depth can be specified.

With all of these basic principles is it now possible to perform trim simulations to find the best suitable resistor pattern for a particular application.

Simulation Cycles

The result of a trim simulation is the *trim characteristic* and its *trim sensitivity* for a given trim path within a given resistor shape. The trim characteristic is defined as the functional dependence of the resistance with the trim path length. It is usually a monotonically growing non-linear function. This function is continuous for each cut path. Multiple trim paths always have a discontinuous trim characteristic. Such discontinuities are kinks that cause a jump in the sensitivity curve.

During the trim simulation the resistance will be calculated for each step (bite) of the trim path. For practical purposes simulations are usually performed in the same manner as real laser trimming. The lasers used in real world applications operate in Q-switched (pulsed) mode with the pulse width being much shorter than the time to next pulse. When the laser beam travels rapidly across the resistor being trimmed the individual pulses overlap creating a cut line through the resistor. To make clean, reliable cuts the pulse spots are usually overlapped by around 70%. Since a typical laser cut width is around 6 microns, this means the bite size is around 2 microns.

Once the width and bite size have been inputted to the simulator, a discrete curve called an *relative trim characteristic* is generated, where the trim function is relative to the initial resistance of the untrimmed resistor. The *trim sensitivity* is the first derivative of the trim characteristic. This curve is important since it shows the achievable resolution for a given cut. The point of the maximum trim sensitivity, s_{sim} is the point of the worst trim resolution. The *trim resolution* is inversely proportional to the trim sensitivity.

For high precision trim purposes the object is to find a trim path that gives the highest trim resolution and simultaneously includes the entire trim range, R that is required. The purpose of multiple trim paths is to have the first set of cuts with low resolution but able to include the entire trim range and then a final cut path with the necessary high resolution. Although multiple trim paths are popular, by necessity several turn and stop/start points are required resulting in an overall complex trim strategy. Several trim simulation runs may be necessary to confirm the practicability of such a trim strategy and to get the needed set of trim characteristic and sensitivity curves.

A single cut path does not need such an effort but forces a long trim path for a large trim interval R, which may enlarge the resistor size to an unacceptable degree. However, if the trim interval is small enough, this strategy is the preferred one.

Trim simulations for each candidate of the initially determined resistor shape set reveal which shapes can fulfill the required specifications and which cannot. This decision is based mainly on the minimum necessary resistor size and the available real estate, A. The minimum resistor size depend on three factors, first on the necessary bite size W that gives the required worst case resolution, second on the maximum current density J_{max} the resistor material can withstand and third on the minimum technological resistor edge length.

The minimum laser spot diameter K and the minimum bite size W are known from the limits set by available laser trim equipment. The diameter K is fixed so that this parameter has the correct aspect ratio to the shape size of the resistor candidate from the set. The bite size for the simulation W_{sim} has to be a low valid value but it can be arbitrary. After the simulation is run over the whole trim interval, the relation of the maximum sensitivity of all possible cut paths s_{sim} to the desired sensitivity $s_t \leq 2\Delta R_t/R_t$, a stretch factor λ_a for all resistor edges is given as follows:

$$\lambda_a = \frac{\max(s_{sim})}{s_t} \frac{W}{W_{sim}} \tag{2}$$

An investigation of the current density J_{sim} under respect of the maximum current I_{max} for the target resistance R_t of a maximum trimmed resistor shape A_R determines a second stretch factor λ_b:

$$\lambda_b = \frac{J_{sim}(I_{max}(R_t), \min(A_R))}{J_{max}} \tag{3}$$

J_{sim} itself is a value calculated during the flux field simulation.
A third stretch factor λ_c may be introduced to express a magnification so that the shortest edge length of the resistor shape is technologically possible. All together, the maximum of all λ_i gives the necessary stretch or shrink factor λ for the shape:

$$\lambda = 1.1 \max(\lambda_a, \lambda_b, \lambda_c) \tag{4}$$

The factor 1.1 is a security factor and may be altered in special cases.
A multiplication of all shape edge lengths with λ creates the minimum possible resistor size and by comparison with the real estate A an assessment of the usability of this pattern can be made. Next it is recommended that a second set of simulations is performed with the real resistor shape and real laser spot size. If the available real estate A is larger than the minimum resistor size it is a good idea to increase λ until the useable space is 'well filled'.

Current Density

In circuit design technology the maximum current density J_{max} for a certain material is used to design a resistor. A flux field simulation is able to create a current density map of a resistor shape. During the simulation the user can pick one J_{sim} from the resistor domain and use this in eq.(3). The maximum current density of a material then searches for the highest current density in the resistor domain. This would be a valid method for a convex domain, with conformal boundary conditions. Unfortunately, a cut into a resistor shape always produces a non-convex domain in which extremely high current densities can exist. In fact each sharp reentry corner into the current flow produces an infinite current density. The mathematical model based on the PDE treats corners at the sub-atomic level, which means that a mathematical infinite current density exists. However, in reality exist no sub-atomic sharp corner, but used layouts are close enough to have very high current densities in these regions that the resistor size becomes unrealistically large if it would used in eq.(3) at this location. From the mathematical point of view the use of an average current density makes no sense because of the infinite terms. Whichever average is used, there always exists an arbitrarily higher current density in such a domain. Surprisingly a mathematically exact average exists in this case but it doesn't fit the normally used J_{max}. As a matter of fact recalculations of realized resistors show that the material can withstand a much higher current density as expected by J_{max}. This may be a question of the heat flow in the structure.
There is no clear answer to the question, which location for the current density is to use for the design. But choosing the geometrical balance point of the smallest "hot zone" that encloses the entire current flow seems to be a practical rule and it meets the previous method.

Example

A resistor with the following electrical parameters is to create by the given processing parameters:

$$R_t = 400\Omega$$
$$\Delta R_t = \pm 2\Omega = \pm 0.5\%$$
$$I_{\max} = 1.5mA$$

$$R_s = 100\Omega / sq$$
$$\Delta R_s = \pm 20\Omega / sq$$
$$J_{\max} = 20A / m$$
$$A = 400 \times 250 \mu m^2$$
$$W = 2\mu m$$
$$K = 6\mu m$$

Based on this is the minimum trim range in accordance with eq.(1) is:

$$\Delta R = 100\Omega / sq \cdot 400\Omega \cdot \left[\frac{1}{100\Omega / sq + 20\Omega / sq}, \frac{1}{100\Omega / sq - 20\Omega / sq} \right] = [333\Omega, 500\Omega]$$

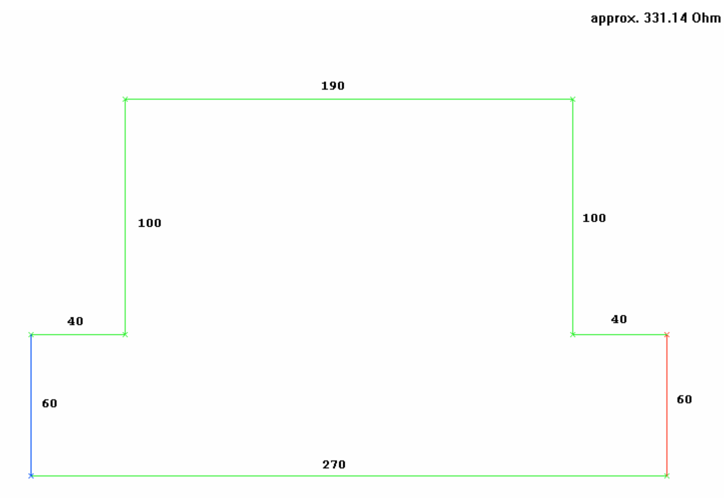

Fig. 3 Resistor shape candidate with approx. 331 Ω

A standard shape for this case is a top-hat resistor with a side cut which usually has a high trim resolution. Figure 3 shows a possible candidate which may be found during the creation cycle. But a side cut cannot enfold the entire trim range because the remaining bar resistor has 450 Ω only.

Not absolute trim paths are indicated because absolute finite cuts cannot achieve this trim task. The decision might be to use a traditional double plunge trim path in bottom-up direction. The idea behind this is that the first plunge cut gives the necessary main target approach and the second one realizes the necessary final resolution. Now a couple of virtual boundaries for the two plunge cuts are to predefine. For instance, the first cut has to be terminated with overstepping of 95% of the target resistance. That means by $380\,\Omega$. The first plunge cut is placed at the symmetry axis of the top-hat and the second one has a constant parallel distance of $40\,\mu m$ to the first one. All these predefinitions are arbitrary and the simulation has to prove their practicability.

The simulator used in the 'absolute' mode so that it hits the target resistance R_t itself. The trim range depends on the sheet resistance tolerance only (see eq.(1)). At least two simulations are necessary to ensure that this trim strategy operates in all cases. The first time for the lowest and the second time for the highest sheet resistance. For all simulation W= W_{sim}= $2\,\mu m$ is used. A sheet resistance R_S-ΔR_S= $80\,\Omega / sq$ provides the following result (Fig. 4):

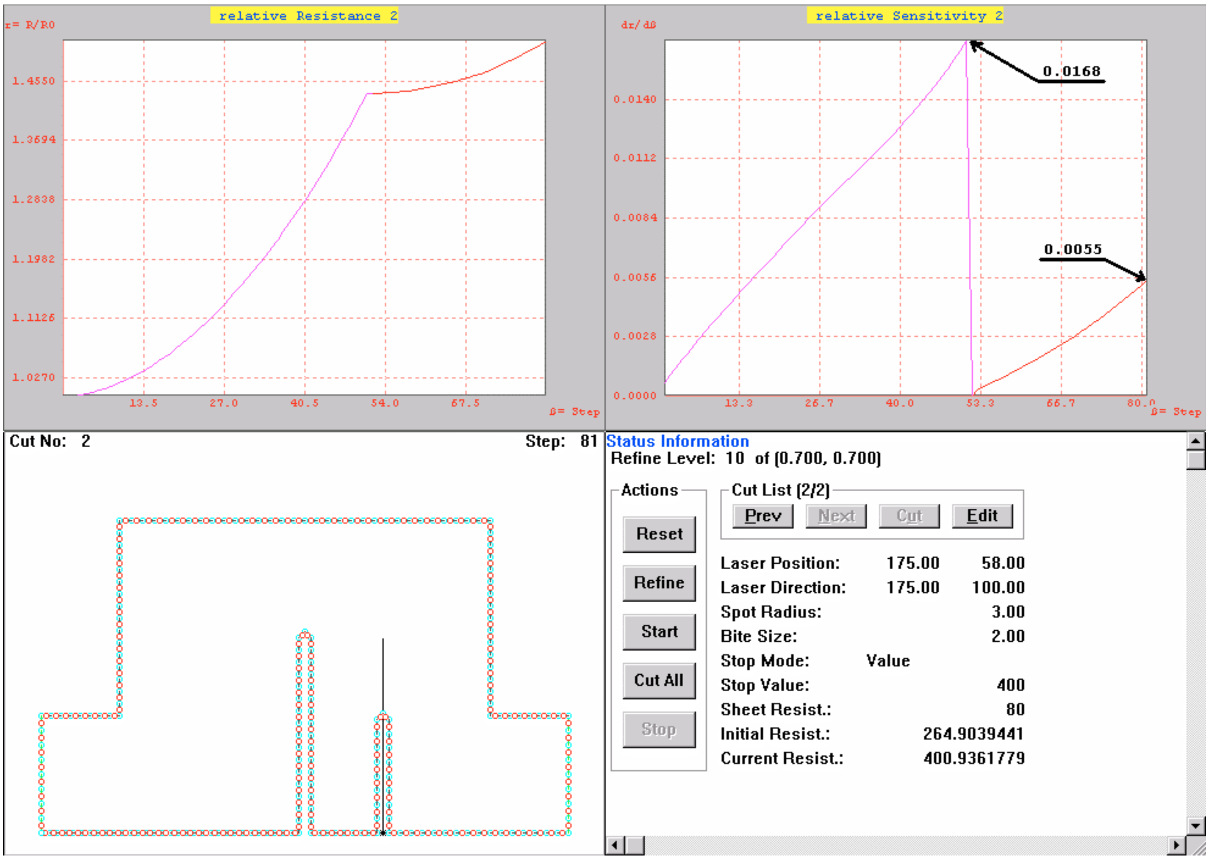

Fig. 4 Simulation result of the double P-cut for R_S-ΔR_S= 80 Ω/sq

$$\max(s^1_{sim}) = 0.0168$$

$$\max(s^2_{sim}) = 0.0055$$

$$W = W_{sim} = 2\mu m$$

$$s_t = \frac{2 \cdot |\Delta R_t|}{R_t} = \frac{4\Omega}{400\Omega} = 0.01$$

$$\lambda_a = \frac{0.0055 \cdot 2\mu m}{0.01 \cdot 2\mu m} = 0.55$$

In this case the first cut stops with a trim sensitivity $s^1{}_{sim}$= 1.68% and this is the maximum along this cut path. This value is much lower than the remaining 5% for the second plunge cut which proves the practicability of the 95% term in this case which must not be overstepped. Also a shrinking by a factor of about 2 (indicated by $\lambda_a = 0.55$) wouldn't affect this result. This further means that all shorter first cuts must also fulfill this condition.

For the upper limit of the sheet resistance (R_S+ΔR_S= $120\,\Omega/sq$) the trim strategy fails. The resistor shape has its layout not far below the lower trim range limit. This causes such a resistor to exceed the 95% term already in the initial untrimmed state. A second cut here is impossible. So the trim strategy has to be altered by using a different trim path if the actual sheet resistance is above the average. The decision depends simply on the initial resistance only. But the average case with R_s= 100 Ω/sq must be checked first:

$$\max(s_{sim}^1) = 0.0095$$
$$\max(s_{sim}^2) = 0.0059$$
$$W = W_{sim} = 2\mu m$$
$$s_t = \frac{2 \cdot |\Delta R_t|}{R_t} = \frac{4\Omega}{400\Omega} = 0.01$$
$$\lambda_a = \frac{0.0059 \cdot 2\mu m}{0.01 \cdot 2\mu m} = 0.59$$

The first cut length is shorter than in the case with $80\,\Omega/sq$ and so the sensitivity condition is fulfilled automatically. The trim sensitivity of the second plunge cut remains below the sensitivity of the first and this preserves the philosophy of this trim path.
In the case of the highest sheet resistance, the resistance of the untrimmed resistor is not far away from the target resistance. That means only a small change is necessary to hit the target. That's the reason why a trim path with a high resolution in the beginning should be chosen. This trim path should be also valid in between the highest and the average sheet resistance whereby the trim sensitivity stays low. That is one quality of finite trim paths and the former trim idea of the side cut will be explored. The simulation delivers the following results for the average sheet resistance case:

$$\max(s_{sim}) = 0.004$$
$$W = W_{sim} = 2\mu m$$
$$s_t = \frac{2 \cdot |\Delta R_t|}{R_t} = \frac{4\Omega}{400\Omega} = 0.01$$
$$\lambda_a = \frac{0.0077 \cdot 2\mu m}{0.01 \cdot 2\mu m} = 0.4$$

Obviously this trim path is qualified to the average sheet resistance. Even the stretch factor is lower than the stretch factors from the double plunge cut simulations. A second simulation with a sheet resistance of $120\,\Omega/sq$ shows that the target is reached after 5 bites by a sensitivity s_{sim}=0.0025. Finally a check for the current density in both trim paths is necessary:

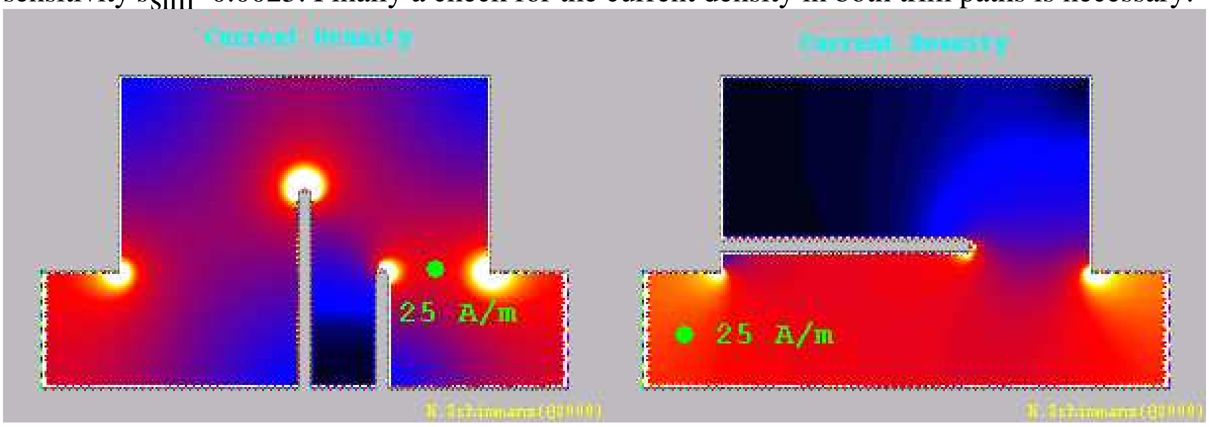

Fig. 5 Current density maps of maximum trim lengths and used sample points (left: 80 Ω/sq; right: 100 Ω/sq)

$$J_{sim}(I_{\max} = 1.5mA, A_{trim}) = 25A/m$$
$$\lambda_b = \frac{J_{sim}}{J_{\max}} = \frac{25A/m}{20A/m} = 1.25$$

The calculation of the final stretch factor λ by using the maximum of λ_a and λ_b results in:

$$\lambda = 1.1 \cdot \max\left(0.59; 1.25; \frac{5\mu m}{40\mu m}\right) = 1.375$$

The comparison of the real estate *A* with the stretched resistor outline confirms the usability of the created resistor shape and its trim strategy.

$$L = \lambda \cdot 270\mu m = 372\mu m < 400\mu m$$

$$H = \lambda \cdot 160\mu m = 220\mu m < 250\mu m$$

In fact a stretch factor λ up to 1.48 is valid for this shape. The use of a higher stretch factor increases the trim resolution and relaxes further the thermal stress of the resistor material. The thermal stress factor is one of the driving factors for the long-term stability of a trimmed resistor. Note that an increase of the trim resolution means also an increase of the necessary number of bites for an average trim. Figure 6 shows the final layout with the two trim strategiesby a used stretch factor of λ= 1.4.

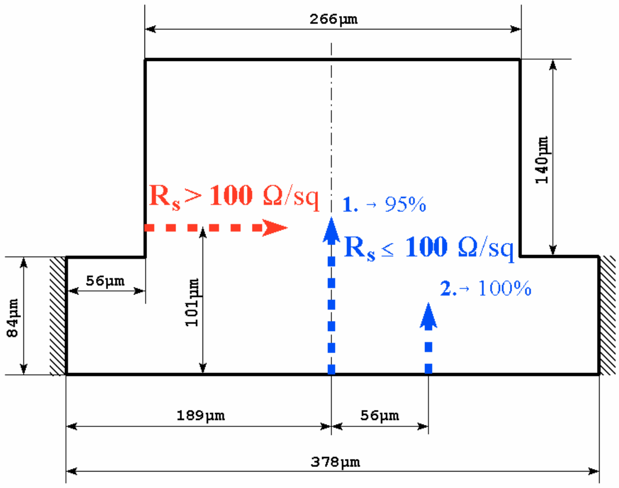

Fig. 6 Final resistor layout and trim strategy

Conclusion

A mathematical model using the appropriate PDE to calculate the resistance provides the freedom to explore any resistor pattern imagineable. No restrictions exist to this. In contrast to other approaches like the square count model, which splits and recomposes the shapes into simpler domains, a numerical model does not need to deal with a resistor shape library. However, the user of a numerical simulator must still have a wide range of experience with resistor design and also a rather deep knowledge of current flux field behavior. Second, such a numerical model isn' t easy to integrate into CAD software without any restriction in the number of different geometry's and trim paths. The conclusion is that such a numerical simulator is a very helpful additional tool to the existing CAD solutions. It is especially useful for the creation of special solutions in certain cases and to refine and confirm CAD results. Ultimately, the trim characteristics derived from the simulations could be used for real time control of the trim equipment itself.

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