Resistance Post-Trim Drift Index for Film Resistors to be Trimmed

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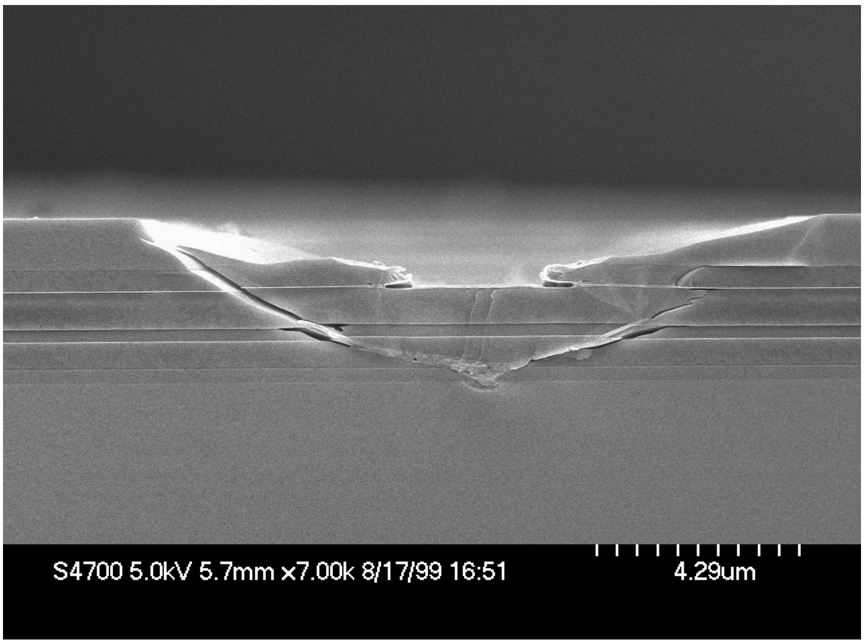
Abstract
This paper discusses a method to evaluate post-trim drifts of laser trimmed film resistor. Based on mathematical flux field computations a drift index is deduced. This index as a part of mathematical laser trim simulations gives an imagination of expected post-trim drifts already on design stage and thereby a method to improve precision and reliability of hybrid IC's by trim strategy design.

Introduction

High precision resistors are responsible for the functionality, capability and reliability of modern hybrid IC's. Laser resistor trimmings on wafer level is the most popular method to achieve the necessary precision who has to compensate various manufacture process variations. The laser trim process itself, however, has an impact on the long term stability of each trimmed resistor. This disadvantage is caused by thermal and mechanical shock the short laser impulse and the following pressure blast cause on one hand and by the Gaussian energy power distribution within a laser beam itself on the other. These effects cannot be avoided completely. To minimize them is a question of the used material system and laser parameter adjustments. The resistance of a trimmed resistor will drift more than a compatible untrimmed counterpart by its aging. The following section of a film resistor demonstrate the destruction of a too high laser power:



Today's high precision requirements made it desirable to predict resistance post-trim drift already on design stage. But because of unknown, and not easy predictable factors of influence an exact model is not to gain. Real world experiments are necessary to get a reliable information on that effect, but an impression can be deduced without them.

Post-Trim Drift Model

The resistance of a film resistor is defined by its shape and thickness and the electrical property of the used film material. The affect of a laser trimming is to change the film geometry by partially vaporizing of the film material. Thus, the shape area becomes smaller and thus, the average current flux field lines within the resistor film becomes lengthen what causes an increase of resistance. In practice cut paths as straight lines into resistor shape will be created to trim a film resistor. The laser operates in pulsed (Q-switched) mode and each pulse (bite) vaporizes a spot of the film material by proper beam energy. An individual laser spot overlap of approx. 70% creates a clean cut path. The energy within the rim zone of a laser beam is not high enough to vaporize the film material because of the Gaussian energy distribution along the laser beam radius. The material will be thermal shocked anyway. This leaves an unstable zone next to each cut path, the so called Heat Affected Zone (HAZ). The material within that zone gets cracked and heated up shockingly by laser energy and anneals amorphous and chaotic. This material will have another electrical characteristic as the film material somewhere else within the shape but it is still a part of the electrical current path. Which concrete characteristic this zone has depends on many factors like on all laser beam parameters, on heat flow issues as well as on the kind of film, substrate and passivation material. In practice the number and all kinds of influences cannot be managed completely. Thus, the material property of the HAZ is usually unknown, also its geometrical spread. The amorphous, chaotic zone character destabilize the resistor in use, because that zone has a lot of microscopic sharp corners. Such corners are reentry ones into the film material. At these points the current density and with it the power density can be extreme if a current flows through the resistor. That means that the electrical current energy conversion into heat is extremely high at those microscopic locations which will change the material structure again. This change is directed to relax the "frozen" mechanical strains in the zone material on such locations. On the other hand this locally heat up can cause thermal stress within its close environment. New cracks can emerge which will heat up too, and so on – but in time the whole heat affected zone becomes more and more relaxed and the relaxation process slows down. In thin film technique, however, we observe that the resistance increases with time, what can be interpreted as a shrink of that zone area. It is also known that the sheet resistivity of the heat affected zone material in thin films is mostly significant lower than the non-affected one [1].

The relaxation process last as long until no microscopic reentry corner is acute enough that the current energy can cause a fast structure change. However, this is a slow process who depends on the amperage, which can constant change for a circuit resistor because of fluctuations of electric signals to be processed and because of resistors self change by its own drift process, and it may last until eternity with a steady declining drift velocity. Another additional influence, of course, is the natural aging of the film material itself and all other circuit components.

Since the concrete electrical characteristic of the heat affected zone is unknown reliable calculations are impossible. On the other hand the knowledge of the drift amount is inevitable to know for high precision laser trim layouts. It makes no sense to trim a resistor onto a high precision if it will ruined by the post-trim drift. From the technological point of view it is not easy to layout a high precision resistor to be trimmed and to predict the post-trim drift effects already on design stage. Experiments to evaluate a long term stability based on many stress cycles and have to be repeated for a lot of different technological conditions, e.g. for maximum and minimum trim path lengths and several sheet resistivities and laser parameters. Thus, the cycle to gather real world data and to reconsider layout would be a costs intense method. To reduce such expenditures some model experiments can be performed and the results can be used for similar resistor shapes by extrapolation of these data [2].

Following a simulation based post-trim drift index will be introduced which can be used to predict the drift range of different trim paths already on design stage for all kinds of resistor patterns. Just one life drift experiment is necessary to determine the meaning of that index value. The index computation is due to numerical flux field simulations which is possible to gather in context with trim design simulations as introduced in [3].

Resistance Post-Trim Drift Estimation on Design Stage

The stationary current flux field is mathematical described by the following partial differential equation:

$$div(\kappa\nabla\varphi) = 0\text{, and boundary conditions of the domain,}$$

where φ is film voltage potential field and κ is materials conductivity. The partial differential equation is analytical solvable in special geometrical cases only. In all other cases, that means especially for all trimmed film resistors, this equation has to be solved numerical. Thus, a numerical solver is needed to compute the resistance of a shape to be trimmed. Then the resistance R itself can be computed by the equation for the spread out resistance:

$$R_{ab} = \frac{\int_{ab} \nabla\varphi d\vec{s}}{\iint_{A} \kappa\nabla\varphi d\vec{A}}$$

for a given domain. It is possible to determine the trim characteristic by changing the shape geometry step by step in accordance to the laser caused film geometry changes. The trim characteristic is defined as the functional dependence of resistance from the trim path length (see [3]).

For an exact calculation of resistance in respect to the heat affected zone, would demand to split the domain and it is to consider a non-harmonious conductivity κ which will change in time as well. Since conductivity, distribution and timely behavior of the heat affected zone material is unknown that kind of calculation cannot be carried out easily.

Now, what is the meaning of a heat affected zone for the current flux field? It just means that parallel to the cut pathway a material with a different conductivity is connected. This conductivity is unknown for us. Despite of that we know that the conductivity of the heat affected film area is usually higher, we can simple assume in a first approach that this material has the same conductivity as the original film material. Or in other words it is just a change of the laser spot diameter or kerf width for the field calculation. A mathematical proof exist for the correctness of this procedure. So we can calculate two trim characteristics for the same cut pathway with two different kerf widths. The difference of both trim characteristics gives us an imagination of the expected drift per step of that cut pathway. If the correct heat affected zone width is known out of an experiment for the used material and trim laser parameters, the real post-trim drift caused by the HAZ will be computed. This difference curve is a monotonously growing one with some kinks at turn and restart points where another cut pathway takes place.

But the more interesting plot is represented by the ratio of that difference to the currently resistance, because it expresses the relative change of the final resistance and is not related to the initial (untrimmed) resistance. This one can be used as post-trim drift index. Such a index curve isn't necessarily a monotonously growing one anymore. However, to estimate the real amount of the post-trim drift we still need one long term stability experiment for the used film material system and laser parameters. Also without that experiment this index will give designers a good decision base which cut pathway fits the concrete high precision requirements at most for a given resistor pattern.

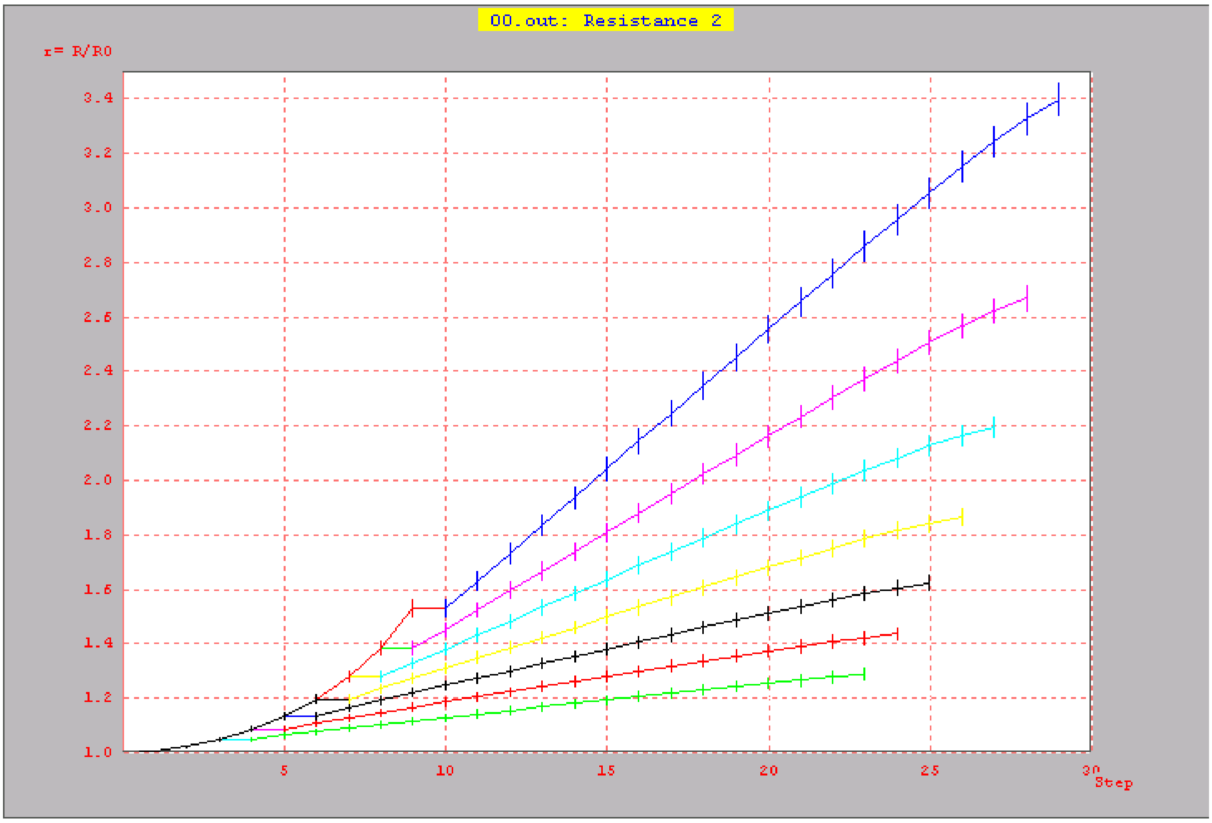
Furthermore, it is possible to gather the power density distribution as additional information during a flux field simulation which can be used to find out how much the heat affected zone is loaded integrally. The 2-dimensional local power density based on the equation:

$$\rho_L = \kappa c (\nabla \varphi)^2$$

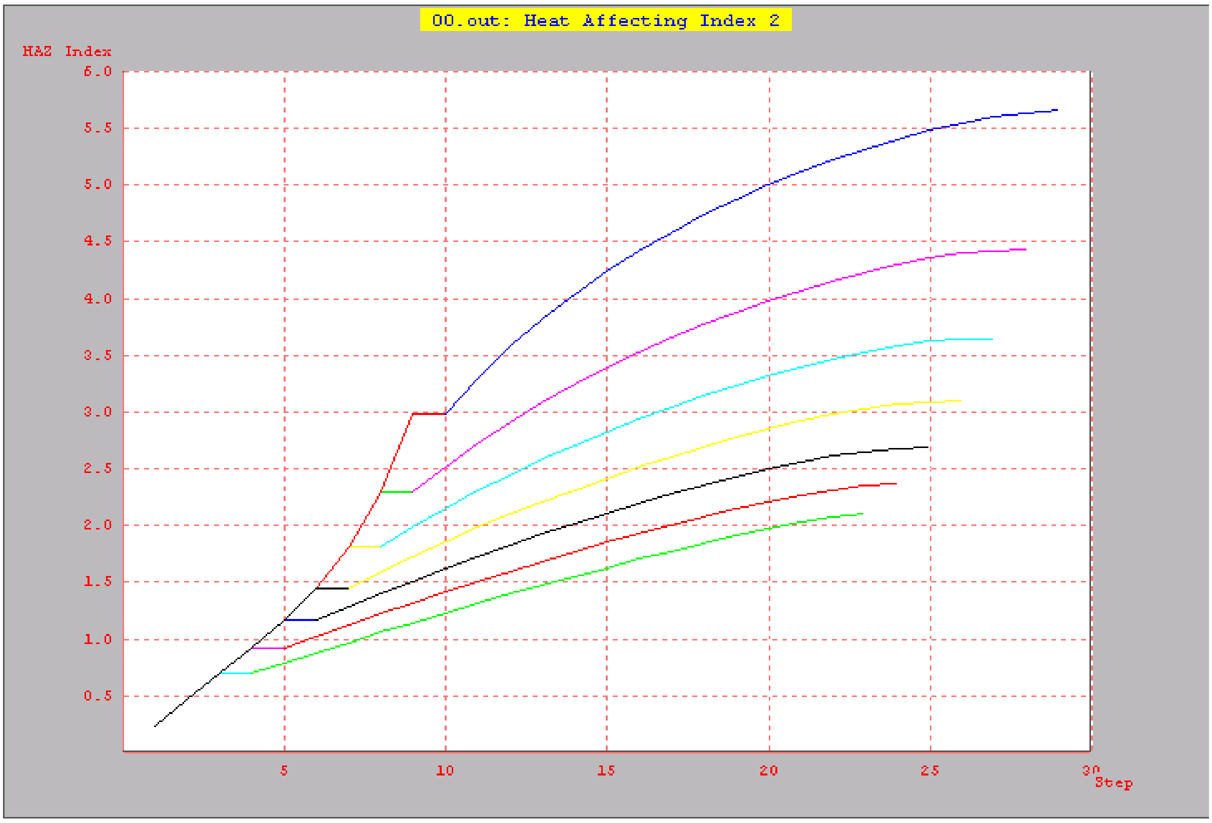
Where c is the film thickness. Since we don't know the power load at any concrete location of that area because of the unknown geometrical structure, this is only a rough average estimation. But it gives us at least a clue how fast the drift might be and also how high the share on the thermal noise index is of this zone. In other words, the higher the average power density of that zone the faster the resistors burn-in will be. The velocity itself, however, depends on power density distribution along the zone. Extreme hot spots indicate a faster drift move as an homogenous distributed power density along the cut pathway by the same zone power density average. The faster drift move is caused by the much higher local temperature what will accelerate the zone relaxation at this point. Next to it must exist at least one much cooler zone region by the same average zone power density. These cool locations may have a less chance to be relaxed during the life time because of missing energy conversion, what could mean a bit lower final drift amount. But their influence of resistance changes is very small. For a closer interpretation the power density map should be inspected, too. However, the existence of extreme hot spots at the laser cut paths indicate a higher trim sensitivity what is in contradiction to high precision trimming goals.

Examples

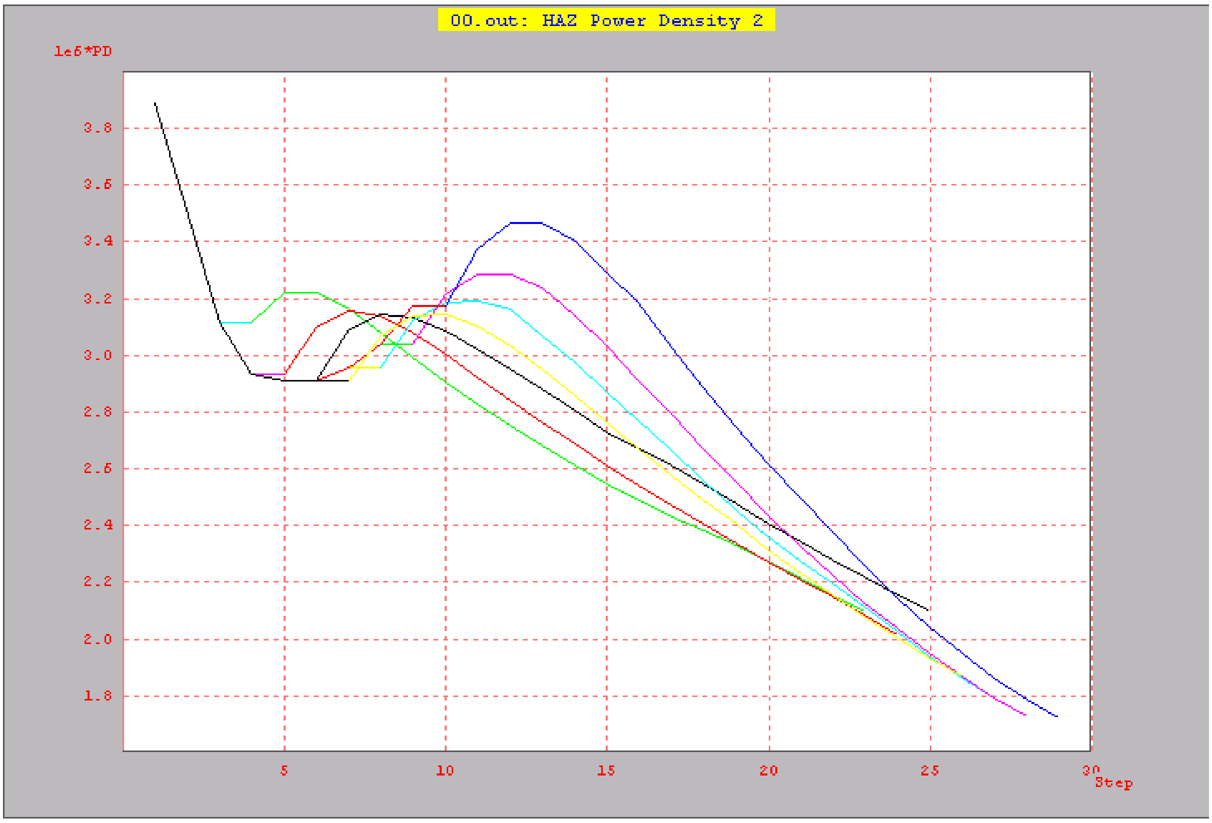
The above mentioned calculations are executed for a bar resistor with the aspect ratio L:W of 2:1. L-cuts as trim pathways with 7 different first plunge depths were chosen. The following plot shows their relative trim characteristics in one view graph. The vertical bars at the graphs present the positive and negative post-trim drift index computed as described above with a scale factor of 1. For film material systems with just a positive drift the negative direction can be ignored and vise versa. The assumption for the simulation was that the laser radius respectively kerf wide changes by 20%. Again, if we would know the real laser spot diameter modification out of a drift experiment, we would obtain here the real post-trim drift values. But also without that knowledge we get a good impression of drift relations between different trim pathways. However, for a first estimation without a new calculation it is also possible to scale the index curve accordingly later. The scaling is valid for a first approach only, because the proportionality is not exactly given. It is obvious that the post-trim drift increases with the cut path length. But this is not necessary always the case, as we demonstrate below, because the index curve is related to the current resistance.



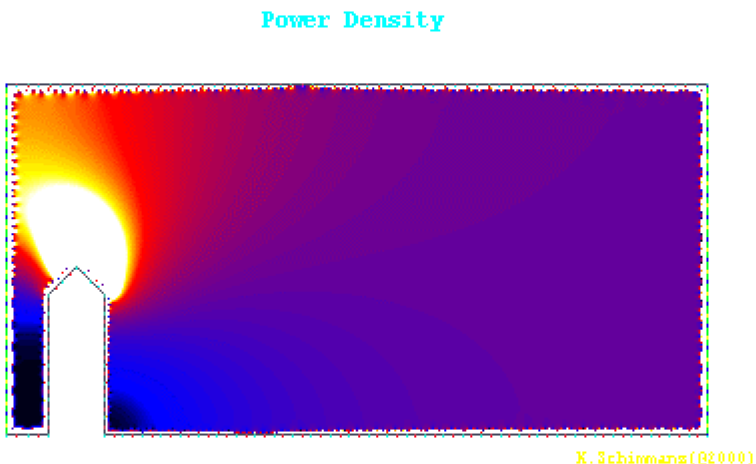
The following view graph shows the percentage index itself. This one looks very similar to the trim characteristic. However, it is not possible to match both of them by stretching or shrinking and the similarity can be violated for other resistor patterns and trim pathways.



The step by step calculation of the average zone power density of these trims produced this plot:

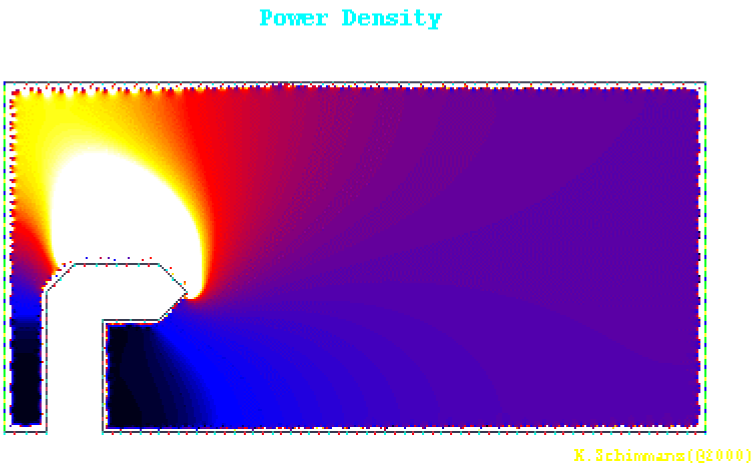


The first plunge cut has a falling gradient toward a minimum and the curve increases again afterward. The following second cuts (the leg) rise the power density to a local maximum and decrease step by step then. We have to take a look into the power density maps first to explain this behavior.

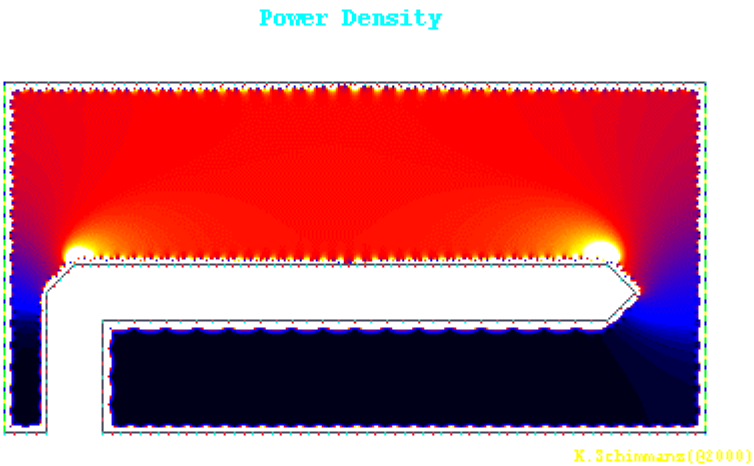


At the top of the plunge we find a huge hot spot. On the cuts left hand side the power density is almost zero. That’s why the average power density decreases with lengthen of the HAZ border first. But the hot spot in top enlarges more and more what will overcompensate this effect later. This is the reason why a minimum in that curve exists.

Now we start with the second cut pathway:

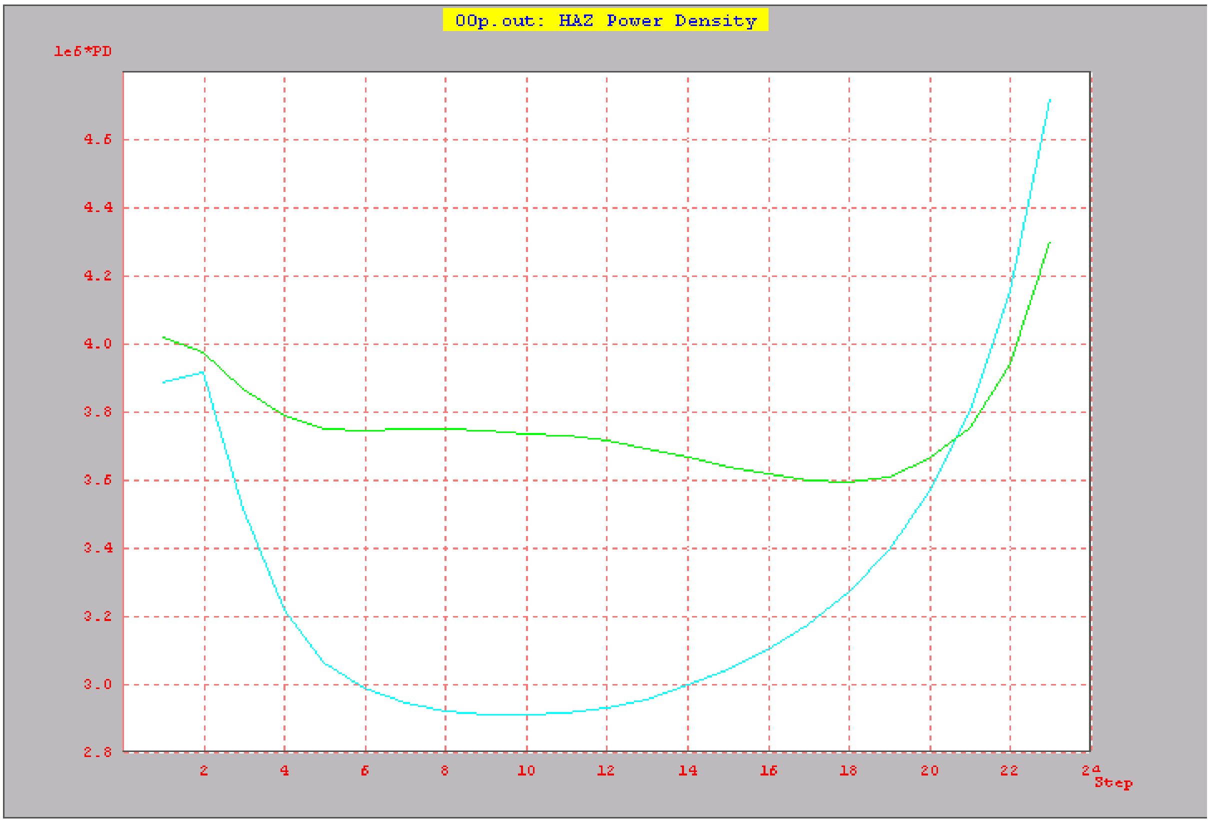


In the beginning the hot spot area will be further enlarged and it will be divided into two separate hot spots later. With cut path progress the power conversion will be distributed over the longer border line, what causes a falling average zone power density curve. At the end of the L-cut the map looks like this:

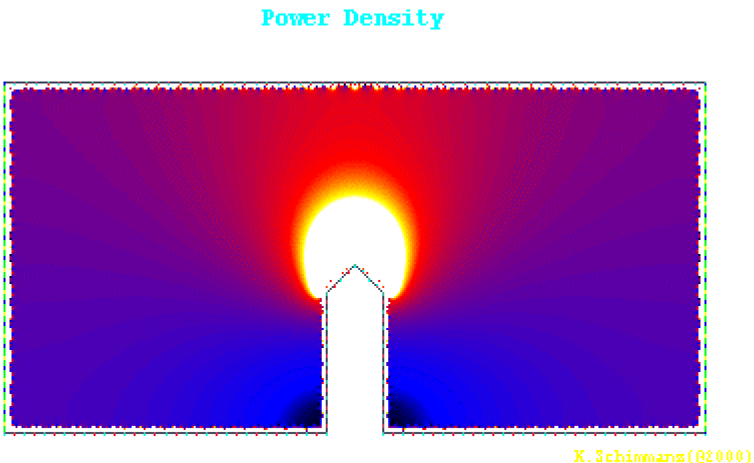


The entire top zone of the resistor is heated up and the two hot spots got much smaller.

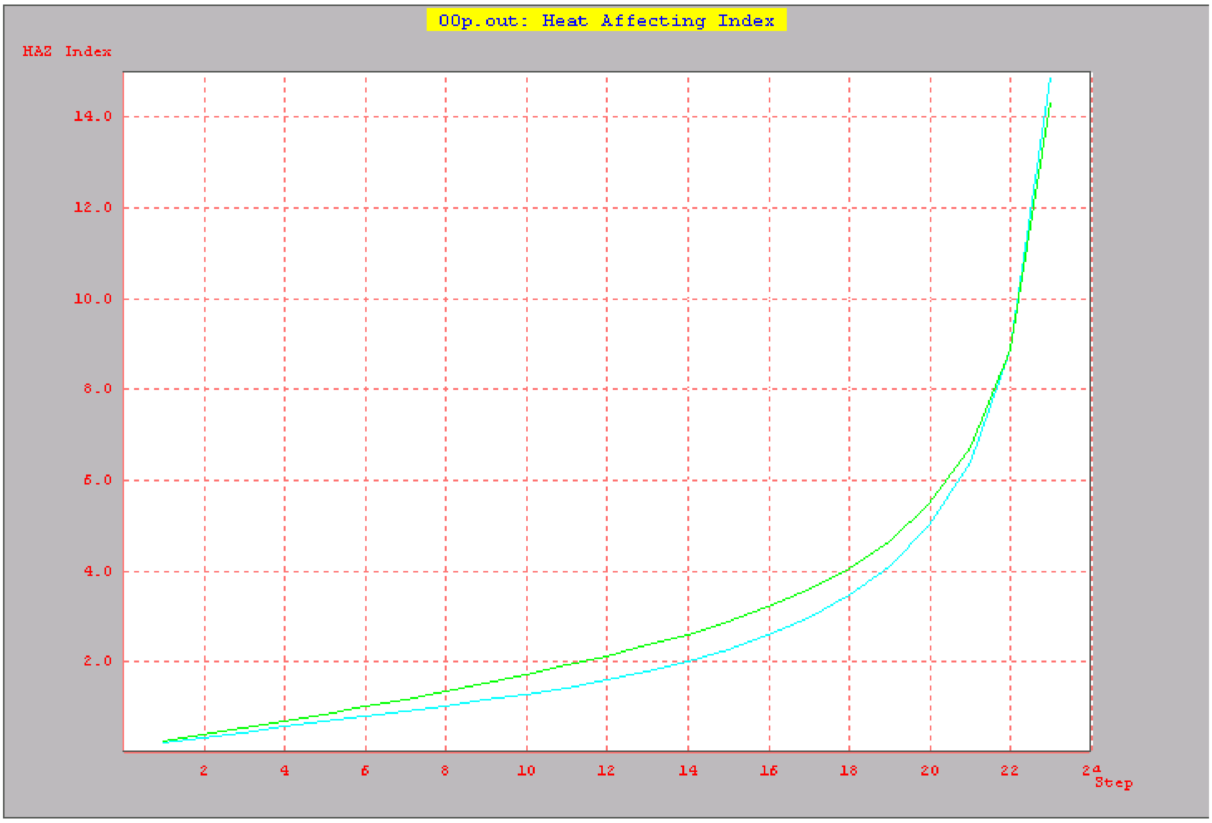
If we compare the first eccentrically plunge cut of the L with a centric one we gain the following average zone power density curves:



The top curve belongs to the centric cut. The inspection of its map gives us the explanation of the difference reasons:

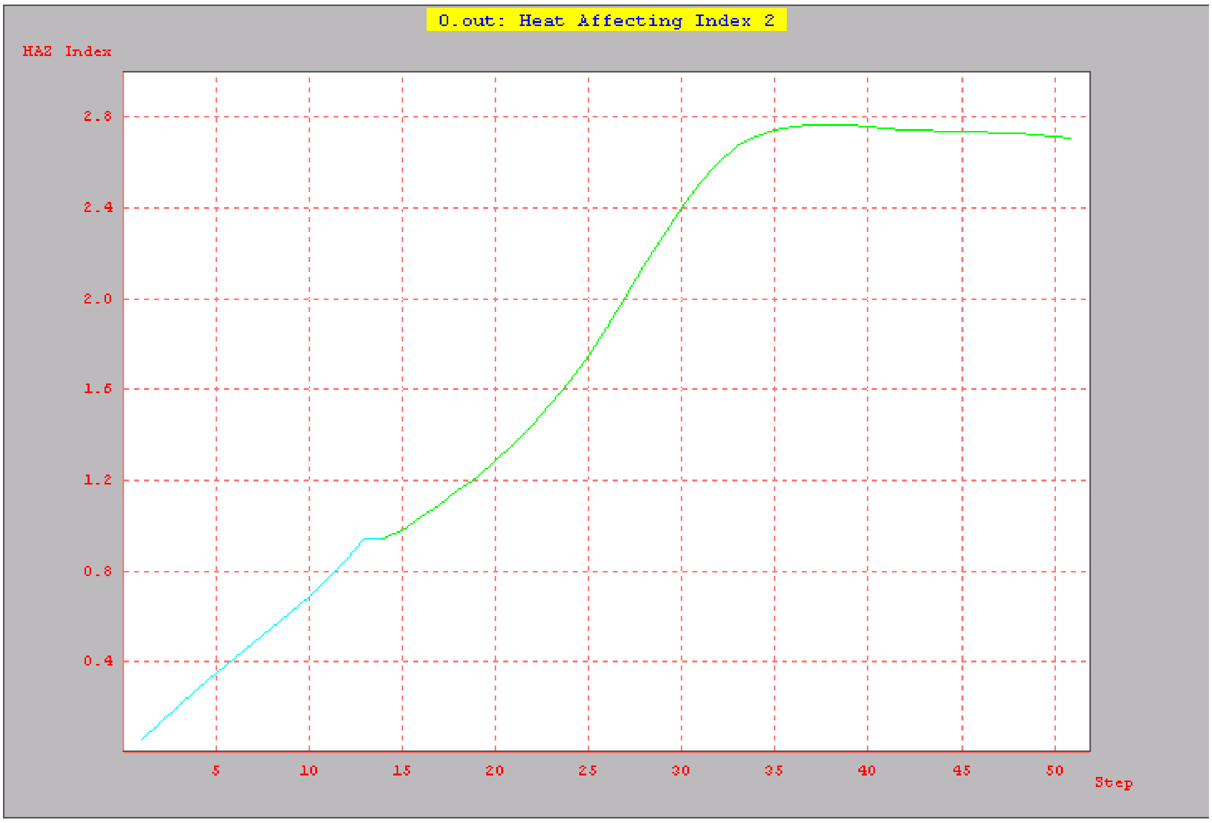


The cooler regions at the cut line are much more intense than at the eccentrically one. So is the average power density mostly higher than for non-centric cuts. The post-trim drift index, however, shows a comparatively small difference:

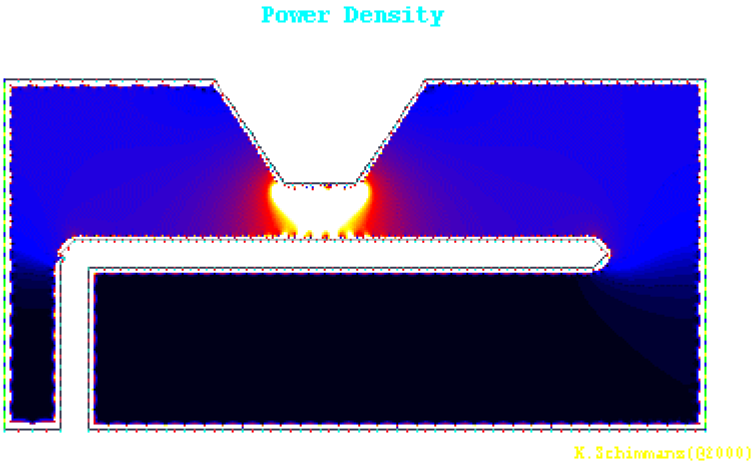


The centric cut pathway has a higher post-trim drift index of course. That’s why an eccentrically one as single plunge cut is to prefer from the drift point of view, too.

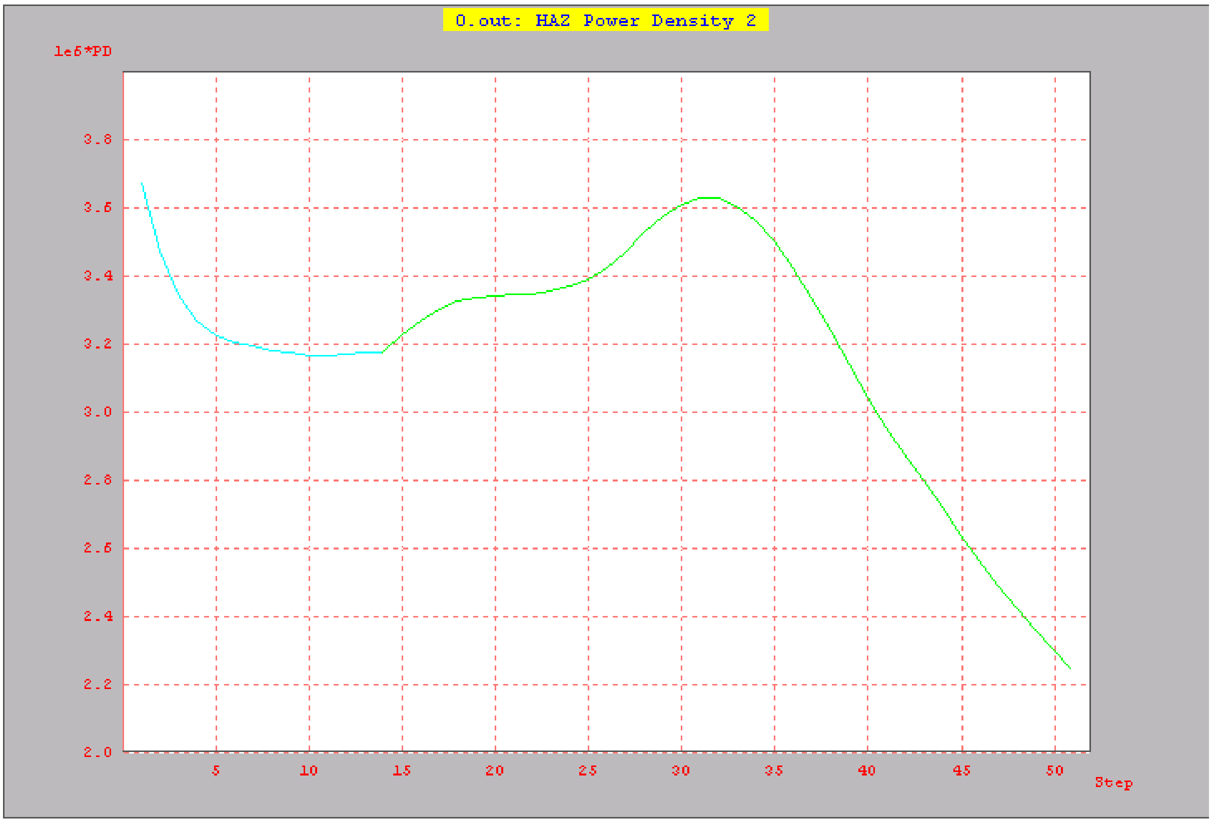
That the HAZ Index not necessarily is a monotonous growing curve demonstrate the following example. First the index:



This can happen if the cut pathway closes and passes another reentry corner of the shape and the current flow has to pass this bottle nag. The power density map shows the application and reveals the reason:



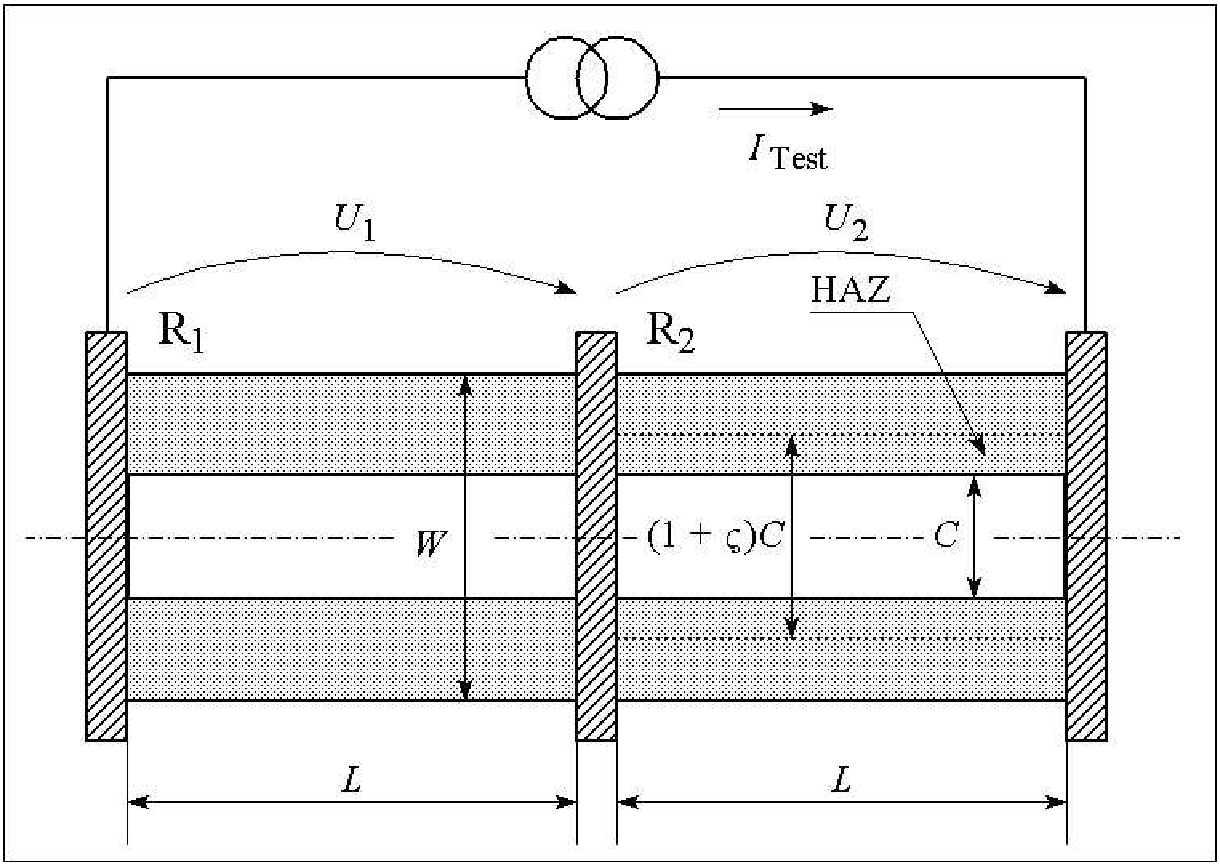
The referred average HAZ power density plot expresses this event too:



If the cut has to be terminated into a already existing hot spot region we also find that the trim sensitivity is at their maximum. Thus, such kinds of trim pathways are not qualified for high precision trimming issues and these situations are to avoid of course.

Experiment to determine the HAZ width

For experimental determination of heat affected zone widths share, ς of the kerf width, C, an arrangement like in the following image can be used for a given material laser parameter system.



Two similarly rectangle resistors has to be produced. Resistor R_1 is to create already with the horizontal structure kerf in the middle. If this is not producible the parallel bars can also moved further from each other or put together. That means it is a bar resistor with length L and width W-C to produce. Whereas resistor R_2 is fabricated as one bar with the width W and the middle hole over the entire length has to be created by the trim laser. The trim laser has to work in the same manner as it will be used for all other future trims. That means with the same overlap, power, and focus, too.

Resistor R_1 is used to eliminate all other drift phenomenon's than the heat affected zone caused ones. Because this one has no heat affected zone but almost the same power density distribution as R_2. Connected to a constant current source the both resistors start to drift. After the resistances are stabilized enough, the heat affected zone part, ς of the kerf width can be calculated by the measured voltages U_1 and U_2 at each resistor as follows.

$$\varsigma = \left(1 - \frac{U_1}{U_2}\right) \cdot \left(\frac{W}{C} - 1\right)$$

Conclusion

In general we found that a longer cut pathway will cause an higher post-trim drift as long this one doesn't pass or produce an additional hot spot with another reentry corner. To reduce the post-trim drift time large cool spots and with it one hot spot along the cut path border are recommended if the zone power density is generally low. In that sense a plunge cut into a resistor close to a power connection seems to be perfect up to a certain trim depth. But the much more precise L-cut into a bar resistor will need a longer time to stabilize. However, the conscious utilization of a fast-drift effect seems to be in opposition to the necessary low trim sensitivity for high precision trimmings. For the case of pair matching is to say that both resistors should have the same overall power density distribution to avoid a different post-trim drift behavior.

Next to the trim characteristic and sensitivity the post-trim drift is an important factor to design high precision film resistors to be trimmed. Today's fast computer technique made it possible to use fast flux field computations during the design process. With it is it possible to use additional information to pick the right trim ways even if we use it for comparative purposes only. Using all this, result in more reliable products and can lead into severe cost savings.

References

[1] Ramirez-Angulo, J., et. al.: Improvement of Laser Trimmed Film Resistor Stability by Selection of Optimal Trim Paths. IEEE International Symposium on Circuits and Systems, Vol. 4/5 VLSI Design and CAD. 11-14 June 1991

[2] Wagner, R.: IC Design for Laser Trimming. SPIE Laser Processing of Semiconductors and Hybrids, 1986, Vol. 611 (LTX Corporation, Westwood MA)

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