

# Applications and Design of Thin Film Resistors

## INTRODUCTION

Resistors are an essential component in any electrical circuit requiring current regulation or voltage division. Implementing resistors with thin film metallization results in a physical structure with high power dissipation capability, small size, and optimal operating characteristics for both DC current and microwave signals. The designer has a variety of material and substrate options available when implementing thin film resistors. Proper choice of these materials and resistor topology result in cost effective designs which reduce parts count. A number of other design and layout considerations discussed here are helpful in improving the manufacturability of thin film resistor circuits.

## RESISTOR DESIGN CONSIDERATIONS

In general, there are four parameters of concern to the engineer when designing a resistor; the resistor value, its change in value over time, its change in value with temperature, and its power handling capability. Secondary considerations include the choice of resistor material, and sheet resistivity. These properties are discussed below for two resistor materials followed by a review of resistor layout practices.

## STEP 1: CHOOSING A RESISTOR MATERIAL

Vishay MIC Technologys thin film resistors are formed by lithographically patterning high-resistance films of tantalumnitride or nichrome deposited on the surface of a wide variety of substrate materials. As with any type of resistor, total resistance is determined by the equation:

$$R = \rho L/Wt$$

Where:

- R = Total Resistance ( $\Omega$ )
- $\rho$  = Bulk Resistivity of resistor material (cm)
- L = Resistor Length (cm)
- W = Resistor Width (cm)
- t = Resistor Thickness (cm)

With thin film resistors, sheet resistance in units of ohms per square ( $\Omega$ ) is often used to specify a film and is calculated as:

$$R_{sheet} = \text{Sheet resistance} = \rho/t (\Omega)$$

Where: = Unit Surface Area of Equal Length and Width

This approach permits easy calculation of thin film resistor values as follows:

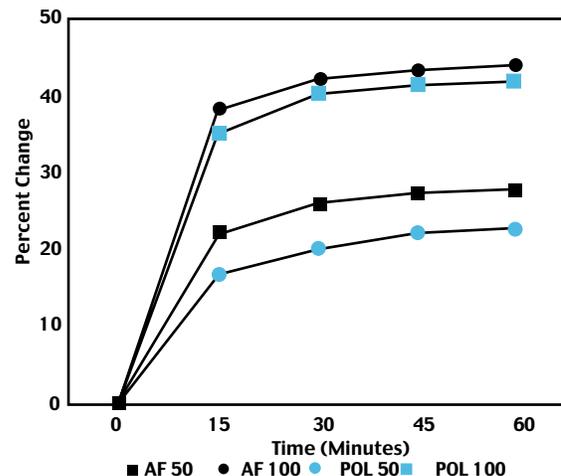
$$R_{total} = R_{sheet} \times \text{Length/Width} (\Omega)$$

Both tantalum-nitride and nichrome resistor films are well characterized and their limitations understood. Likewise, the deposition processes used to create these films have been described extensively in the literature. In general, deposited films in excess of a few hundred angstroms can produce sheet resistivities of 10 to 150 ohms/square for tantalum nitride, and 10 to 350 ohms/square for nichrome. These resistivity values are achieved by stabilization baking the films in air for varying amounts of time as illustrated by the curves in Figure 1 for both polished and as-fired alumina substrates. The baking process creates an oxide layer from the surface resistor material, which self-passivates the resistor, preventing future changes in value.

The knee of the stabilization curve in Figure 1 is the point at which the oxide growth rate has reduced to a minimum and the resistor film thickness is at a maximum, making this the optimal point to stop the annealing process. Long term stability of properly stabilized and trimmed tantalum-nitride and nichrome resistors results in significantly less than a 0.5% change in value over 1000 hours at 125C (in air). Although it has a higher TCR, tantalum nitride resistors have overtaken nichrome in usage volume due to their more flexible stabilization baking profiles.

To ensure an optimal resistor for your application, be sure to supply MIC Technology with the maximum time and temperature exposure for your application. The above discussions have assumed a uniform resistor film and a completed resistor of ideal dimensions, per design. In general, sheet resistance can vary by 25% within a lot of material as a function of deposition environment, surface quality, substrate material, and other factors. This reality dictates that resistors be laser trimmed to final value and is a preferred approach over fired-to-value requirements. Standard laser trimming achieves 10% tolerances on completed resistors while tolerances of  $\pm 1\%$  of design value are routinely achieved with proper resistor layout. Tighter tolerances can be obtained on a specialized basis for certain resistor designs.

Figure 1: Typical Stabilization Curve for Tantalum-Nitride



The above parameters contribute to what could be termed the static resistor value, while the deposition process, intrinsic material properties, and film stoichiometry all contribute to changes in resistance values as a function of temperature, a dynamic property. These changes are quantified by the temperature coefficient of resistance (TCR), defined as:

$$TCR = \frac{(R2-R1) \times 10^6 \text{ ppm/C}}{R1 (T2-T1)}$$

Where:

- R2 = final resistance ( $\Omega$ )
- R1 = initial resistance ( $\Omega$ )
- T2 = final temperature ( $^{\circ}\text{C}$ )
- T1 = initial temperature ( $^{\circ}\text{C}$ )



As an example, a 50 ohm resistor at 25°C which drifts to 49.5 at 150C has a TCR of:

$$\begin{aligned} \text{TCR} &= \frac{(49.5-50) \times 10^6}{49.5(150-25)} \\ &= -80.8 \text{ ppm/}^\circ\text{C} \end{aligned}$$

The TCR of tantalum-nitride is typically measured within a range from -25 to -150 ppm/°C, while the TCR of nichrome is in the range -25 to +25 ppm/°C. Tolerance on this value for a given material and process lot is readily maintained within a ±25 ppm/°C window. The resistor properties discussed above are summarized for alumina substrates in Table 1. Table 2 highlights other substrate materials available and their associated resistance ranges.

**STEP 2: REVIEW POWER DISSIPATION REQUIREMENTS**

For years, a number of rules of thumb for safe power dissipation in thin film resistors have been passed throughout the engineering community. Rather than employ this typically inaccurate information, the designer should consider resistor film temperature, the critical parameter in determining the failure point of a resistor. This temperature is affected by resistor geometry, total circuit power dissipation, proximity to other dissipative elements, type of substrate material and the heat sinking used. Obviously, a complete thermal analysis is required to precisely determine the resistor temperature rise.

For good stability, the maximum, steady-state resistor film operating temperature should stay within several degrees of the of the 125°C stability rating temperature for non hermetic environments. For every 10°C rise in resistor temperature over this value, resistor stability degrades by a factor of 2 (in air). Specifically, a resistor value which drifts by 0.5% at 125°C will drift as much as 1% for each extended temperature excursion to 135C. An important point to be made, however, is that this value applies in an air environment because of continued oxide growth into the resistor film. In hermetic environments, these temperature excursions have little impact on stability while at significantly higher power levels, other physical phenomenon such as electromigration, may cause resistor failure. A highly conservative design rule for hermetic environments, therefore, is to limit resistor film temperature to 130°C maximum. An example of temperature rise as a function of applied power will best illustrate this point:

A 50 ohm resistor, 15 mils by 15 mils, deposited on a 15 mil thick alumina substrate is soldered to a regulated heat sink within a hermetic enclosure. We begin with a baseplate temperature controlled to 85C and an applied power of 1 watt. Entering this information into a 2D thermal simulator results in a resistor temperature of approximately 114°C. At this point, the power density in the resistor is 1 watt/.000225 in<sup>2</sup> or 4444.4 watts/in<sup>2</sup>! The resultant operating temperature is still within a range where long term stability is not compromised. Measured results taken with a fluoroscopic probe support this conclusion within 5 degrees and indicate a theoretical limit for this resistor of nearly 8000W/in<sup>2</sup>.

**TABLE 1 : RESISTOR PROPERTIES, 99.6% ALUMINA**

Material	TCR (ppm/°C)	Standard Sheet Resistivity (Ω)	Passivation	Stability*	Tolerance**
TaN	-125 ± 25	25 - 125	Self. Passiv.	< 0.5%	1 - 10%**
NiCr	0 ± 25	50 - 250	Self. Passiv.	< 0.5%	1 - 10%**

\*1000 hrs @ 125C, \*\*± 10% Standard

**TABLE 2 : RESISTOR PARAMETERS FOR ADDITIONAL SUBSTRATES**

Substrate Material	Standard Sheet Resistivity (Ω)	Optional Sheet Resistivity (Ω)	TaN	NiCr	Comments
Beryllia	25 - 100	Check Factory	yes	yes	Laser trimmable to 1%. Design to allow up to 50% width Reduction
Aluminium Nitride	25 - 100		yes	yes	Laser trimmable to 1%. Design to allow up to 50% width Reduction
Quartz	25 - 200		yes	yes	—
Sapphire	25 - 200		yes	yes	—

Clearly this power density example exceeds the rules othumb most engineers are familiar with. The power density values indicated in Table 3 are based upon several data samples and should only be used as a guide. Beryllia, with its higher thermal conductivity is perfect for higher power resistors, enabling power densities approaching 20,000 W/in<sup>2</sup>. For any temperaturecritical design, however, a complete thermal analysis should be done to ensure long term reliability and stability.

**TABLE 3 : RESISTOR POWER HANDLING EXAMPLES**

Substrate & Thickness (mils)	Resistor Material	Res Dim (mils)	Power Applied (watts)	Base Temp (°C)	Res Temp Simulated (°C)	Res Temp Measured (°C)	Power Density (W/sq in)
A1 <sub>2</sub> O <sub>3</sub> .015"	TaN (50Ω)	15 x 15	1	85	114.5	118	4,444
BeO/.010"	TaN (50Ω)	25 x 25	9	85	99.8	106	14,400

**STEP 2: REVIEW POWER DISSIPATION REQUIREMENTS**

The previous sections have provided the designer a background in resistor materials, sheet resistance, and tolerance issues. The designer has a number of layout options available at this point and should review the following rules to create conveniently sized, manufacturable resistors.

### Calculating Resistor Dimensions

As explained in Section 1, thin film resistors are commonly characterized by the normalized parameter called sheet resistivity, defined previously in units of ohms per square ( $\Omega$ ). Physical resistor sizes are easily calculated by dividing the resistor value required by the sheet resistance desired and then, based upon power-handling requirements and available space, choosing a convenient square size.

As an example, the designer needing a 200 resistor using a 25 $\Omega$  resistor film calculates the number of resistor squares required as:

$$\begin{aligned} \text{Squares} \\ \text{Required} &= 200\Omega / 25\Omega = 8 \end{aligned}$$

If this resistor was required to handle only a few milliamperes of current in a digital application, the designer may choose a 0.002 x 0.002 (50 $\mu\text{m}$  x 50 $\mu\text{m}$ ) square, resulting in a resistor length as follows:

$$\begin{aligned} \text{Resistor Length} &= 8 \times 0.002 \\ &= 0.016 \text{ (400}\mu\text{m)} \end{aligned}$$

Thus, the 200 resistor is achieved with a 0.002 x 0.016 dimension. For resistors employing 90 degree corners, the corner square is valued at 50% of a standard square resistance, requiring a length compensation in the completed resistor design. The above resistor example would thus require 8.5 squares if it had one 90 degree bend. These requirements are illustrated in Figure 2 for simple resistors designed using a 100 $\Omega$  film. The previous calculation approach is used to determine resistor sizes from electrical design values using a starting square size sufficient to handle the power in each case. After completing a first pass calculation of resistor sizes, the following fundamental guidelines should be used for the initial thin-film circuit layout:

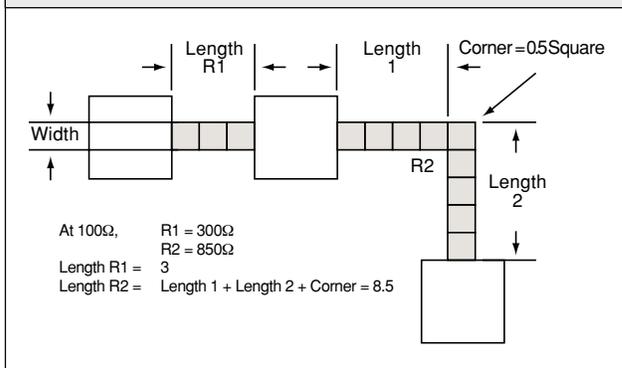
### Limit Designs to Inboard-Style, Type-1, Resistors

All of the resistor styles discussed and illustrated in the upcoming section incorporate an inboard, or Type-1, resistor layout which dictates that the resistor material is inboard of the conductor material by a predefined distance. An alternate layout approach known as Type-2 style resistors, permits the resistor film to lie co-incident with the adjacent conductor pads as shown in Figure 3. MIC Technology design rules permit only Type-1 resistors due to their reduced dependence on masking accuracy and improved manufacturing flexibility. MIC Sales Engineers can provide support in converting your Type-1 designs to Type-2 designs if required.

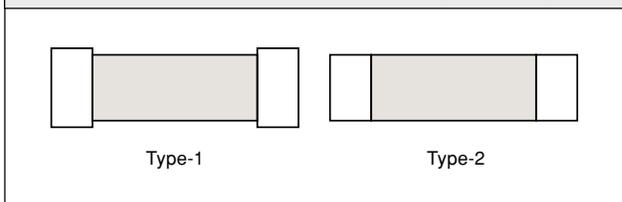
### Use Square or Rectangular Shapes for Low to Moderate Resistor Values

This approach facilitates simplicity and creates testable chains of resistors separated by probe pads. Each resistor, as measured from probe pad to probe pad, should be laid out to 100% of desired value. Typical applications include binary resistor arrays and bias networks for amplifiers similar to that shown in Figure 2.

**FIGURE 2: SAMPLE RESISTOR CALCULATIONS**



**FIGURE 3: TYPE-1 & TYPE-2 RESISTORS**



### USE A SERPENTINE APPROACH FOR HIGH VALUED RESISTORS

Higher-valued, low-power resistors are often laid out in a serpentine fashion consisting of a narrow, meandering resistor trace as shown in Figure 4. Serpentine resistors may be laid out as an etched pattern per MIC Technology design rules but, because each 90 degree corner provides only 50% of the resistance of a series square, its total length must be compensated to achieve the proper value. This approach becomes cumbersome for large resistors. The preferred method for designing serpentine resistors uses a large block of resistor material into which a trim laser makes plunge cuts alternating from either side of the resistor to achieve the final resistance value. The design process begins with the engineer choosing a unit square resistor size based upon resistor current handling requirements. The unit square is then widened by 1.5 mils to compensate for the laser kerf (or cutting path). The resistor is then sized by creating a matrix of these compensated squares placed edge to edge. The design is completed by adding at least one square of material to each end of the resistor to connect with the adjacent conductor pad. Prior to trimming, the resistor will typically resemble a top-hat, with the brim of the hat connecting to the adjacent conductor traces. A final, simple way to design low current serpentine resistors is to use squares that are 5mil<sup>2</sup>, stacked side by side in the same fashion as the previous method. Although this approach results in a smaller resistor area than the first design method, adequate space still remains for laser trimming. For serpentine resistors handling higher currents, however, the former method, which bases square size on power requirements, must take precedence. Both of these design methods may also employ a link trimming approach to fine-tune the resistor value as illustrated in Figure 4.

**RE-OPTIMIZE SHEET RESISTANCE VALUES IF EXTREMELY LARGE OR SMALL RESISTORS HAVE BEEN CREATED**

In the event that a high sheet resistance has been chosen, it is possible that extremely low valued resistors will become prohibitively small, making them highly sensitive to etching tolerances. A complementary situation exists for low sheet resistance values with high valued resistors. In the first case, a lower sheet resistance will result in optimal resistor dimensions, while a higher sheet resistance will solve the problems of the second case. A highly conservative rule of thumb for sheet resistance choice says that if any resistor designs in a circuit layout are less than half a square in size, the sheet resistance may be too high. In some instances, designers may have difficulty achieving very low and very high resistor values on a single circuit using a single sheet resistivity. MIC Technology has the unique capability to provide two different sheet resistivities on a single circuit, giving the designer more flexibility. Check with your MIC Sales Engineer for more information on this capability.

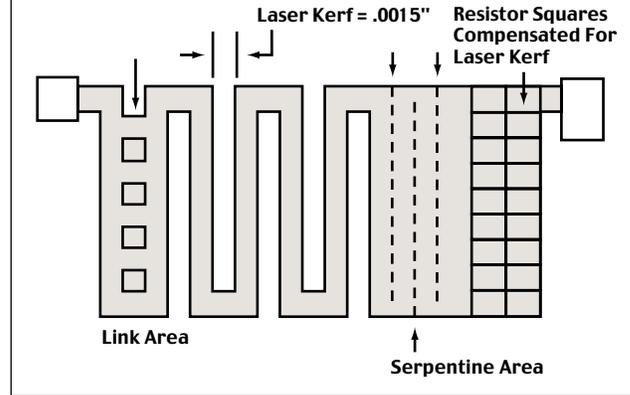
**ADD APPROPRIATE ADDITIONAL LENGTH TO COMPENSATE THE VALUE OF ODD SHAPED RESISTORS**

As noted previously for serpentine resistors, corner squares are computed as 50% of the value of a standard square, requiring the addition of half a square of length to achieve the desired final value. The values of curved and odd shaped resistor features are calculated by numerical integration of series and parallel resistor segments where  $R_{total} = r1+r2 +$  for series segments and  $1/R_{total} = 1/r1 + 1/r2 +$  for parallel segments. The result of these calculations may require the addition or removal of resistor material from the layout to achieve the proper value.

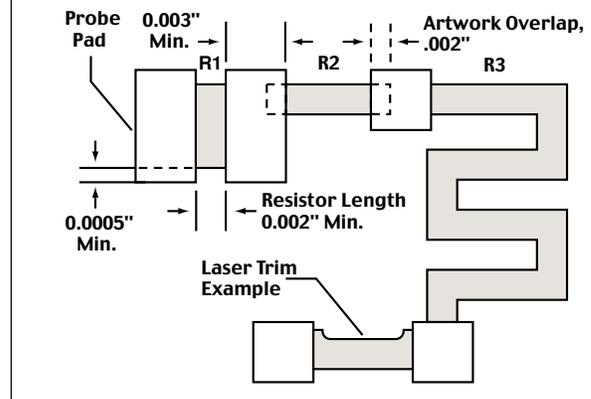
**ADD RESISTOR PROBE PADS AND OVERLAPS PER DESIGN RULES**

No matter what the style, each side of a resistor must terminate in a conductor or probe pad, which is a minimum of 0.5 mil (12.5µm) per side wider than the resistor. The preferred conductor overlap is 1 mil (25µm) per side if space permits. This overlap, perpendicular to the direction of current flow, allows for minor misalignments in the resistor masking step. To ensure adequate contact area for resistor probe tips during trim, the resistor probe contact pads must be a minimum of 0.003 (75µm) per side. Each end of the resistor mask (or resistor CAD layer) must also extend 2 mils (50µm) into the probe pad per MIC Technology design rules. These overlap and probe pad requirements are highlighted in Figure 5.

**FIGURE 4: SERPENTINE RESISTOR WITH TWO AREAS FOR LASER TRIM**



**FIGURE 5: PROBE PAD AND ARTWORK OVERLAP REQUIREMENTS**



**CONSIDER LASER TRIMMING ISSUES**

With respect to laser trimming of resistors, a maximum of 50% resistor width reduction is considered acceptable per MIL-STD-883. Unfortunately, this specification does not take into account the power handling capability of a resistor, so the engineer should. When designing a high power resistor, two options available include enlarging the resistor 50% to accommodate a worst-case trimming scenario, or consult with your MIC Sales Engineer to request, on a specialized basis, a maximum trim limit specification. MIC Technology uses a scrub trim approach on all non-serpentine resistors unless requested otherwise, resulting in a constant width resistor after trim. This approach, illustrated in Figure 5, results in a highly symmetrical resistor which maintains excellent RF performance in microwave applications. To speed up the trimming process on high volume, low frequency designs, a plunge trimming approach is available. As mentioned previously, high valued serpentine resistors in low frequency circuits, most often employ plunge cuts alternating from both sides of the resistor. General layout guidelines for resistors are reviewed in Table 4.

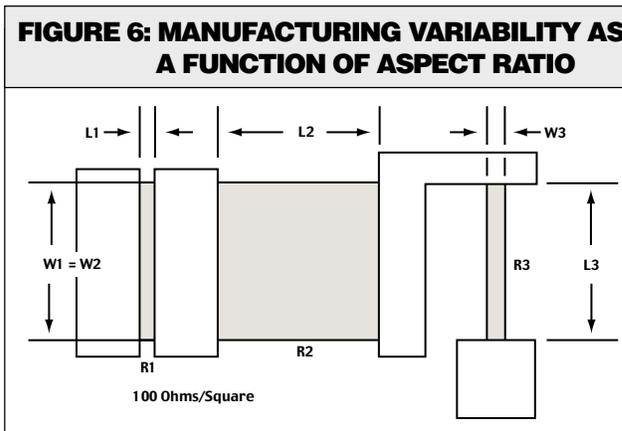
### MANUFACTURING VARIABILITY

After reviewing the previous information it should become evident that control of sheet resistivity and pattern fidelity are the critical process issues in building thin film resistors. The designer can, however, mitigate a great deal of the difficulty by using layouts which are more tolerant of process variations. It should be apparent that the smaller the geometry of a resistor the greater the change in value due to dimensional variations. This problem is most severe in a design incorporating a wide range of geometries in that resistor values diverge rapidly with increasing process variability. Figure 6 illustrates this point, with high valued, narrow resistors being sensitive to resistor overetch and wide, low-valued resistors being sensitive to conductor overetch. Specifically:

- R1 will rapidly increase in value due to overetched conductors.  
For example: A 0.001 long, 0.010 wide resistor of 100 ohms per square will increase in value by 40% if the conductor is overetched by 0.0002 on each side.
- R2 will provide an optimal balance between conductor or resistor etching tolerance.  
For example: A 0.010 by 0.010 resistor of 100 ohms per square will vary in value by only 4% for resistor or conductor tolerances of 0.0002.
- R3 will change in value rapidly due to overetch of the resistor film.  
For example: A 0.001 wide, 0.010 long resistor of 100 ohms per square will vary 67% in value if the resistor is overetched by .0002 per side. In general, the designer can minimize fabrication problems by:
  1. Designing Type-1 (resistor inboard) rather than Type-2 resistors.
  2. Using minimum sheet resistivity values.
  3. Maximizing resistor dimensions or designing resistors larger than a half a square.
  4. Incorporating dimensional consistency among the resistors.
  5. Laying out resistors to 100% of nominal value.

**TABLE 4: GENERAL RESISTOR LAYOUT GUIDELINES**

Parameter	Value	Inches (μm)	Comment
Resistor Style	Type-1		Resistor Inboard of conductor
Max # of Sheet Resistives	2		
Min Resistor Dimension	.002 x .002 (50 x 50)		
Min Probe Pad Dimension	.003 x .003 (75 x 75)		
Conductor/Resistor Overlap	.0005 (12.5) per side min. .001 (25) preferred .002 (12.5) per end		Perpendicular to Current Flow Parallel to Current Flow (On Resistor Mask)
Layout Dimensions (Standard Resistor) (Serpentine Resistor)	100% of value 100% of value plus laser kerf or 5 mil <sup>2</sup> (3160 μm <sup>2</sup> )		Based upon L/W x R <sub>sheet</sub> Based upon 1.5 mil (32.5 μm) laser kerf
Trim Style	Scrub		Optional Plunge
Resistance per Square	100% of R <sub>Sheet</sub>		—
Nominal Square	50% of R <sub>Sheet</sub>		90° Serpentine Corners
Corner Square	50% of R <sub>Sheet</sub>		—
Irregular Shapes	$R_{Total} = \sum R_{Series} + \sum 1/R_{Parallel}$		—





**SUMMARY**

Thin film resistors offer the designer a broad degree of flexibility in circuit design. Proper choice of material and layout approach enables the designer to achieve resistors with exceptional microwave performance and power handling capability. Furthermore, Vishay MIC Technology's considerable experience with single and dual sheet resistivity circuits permit the designer to reduce component count and assembly cost in today's PIMIC™ designs.

**RESISTOR DESIGNER'S QUICK REFERENCE GUIDE**

<b>RESISTOR PROPERTIES - 99.6% ALUMINA</b>					
Material	TCR (ppm/°C)	Standard Sheet Resistivity (Ω)	Passivation	Stability*	Tolerance**
TaN	-125 ± 25	25 - 125	Self. Passiv.	< 0.5%	1 - 10%**
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\*1000 hrs @ 125C, \*\*± 10% Standard

<b>RESISTOR PARAMETERS BY SUBSTRATE</b>					
Substrate Material	Standard Sheet Resistivity (Ω)	Optional Sheet Resistivity (Ω)	TaN	NiCr	Comments
Beryllia	25 - 100	Check Factory	yes	yes	Laser trimmable to 1%. Design to allow up to 50% width Reduction
Aluminium Nitride	25 - 100		yes	yes	Laser trimmable to 1%. Design to allow up to 50% width Reduction
Quartz	25 - 200		yes	yes	—
Sapphire	25 - 200		yes	yes	—

<b>RESISTOR LAYOUT GUIDELINES</b>			
Parameter	Value	Inches (μm)	Comment
Resistor Style	Type-1		Resistor Inboard of conductor
Max # of Sheet Resistives	2		
Min Resistor Dimension	.002 x .002	(50 x 50)	
Min Probe Pad Dimension	.003 x .003	(75 x 75)	
Conductor/Resistor Overlap	.0005 (12.5) per side min. .001 (25) preferred .002 (12.5) per end		Perpendicular to Current Flow Parallel to Current Flow (On Resistor Mask)
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Trim Style	Scrub		Optional Plunge
Resistance per Square	100% of R <sub>Sheet</sub>		—
Nominal Square	50% of R <sub>Sheet</sub>		—
Corner Square	R <sub>Total</sub> = ΣR <sub>Series</sub> + Σ1/R <sub>Parallel</sub>		90° Serpentine Corners
Irregular Shapes			—

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