Thin Film Technology Corp.

Measuring the Effects of Current Crowding on PCBs with TFT's 4T CSR

Four-terminal resistors contribute to measurement accuracy, and various designs exist for their construction. Resistors such as Thin Film Technology Corp's (TFT) CPA series perform better in high power applications due to its high heat dissipation capabilities. Resistors with a four-corner electrode design, such as TFT's WRL series, provide more precise readings due to its symmetrical electrode design. The benefit of this design allows measurements to be taken from any point and orientation

A study by TFT's engineers investigated the factors that contribute to variations in resistance following the mounting of the component to a PCB. Factors that were considered are excitation location of current flow, resistor misalignment, and PCB copper thickness. These all influence the current crowding experienced in the resistor, meaning that the current distribution through the resistor is uneven. This effect can be seen in current density simulations of the CPA 0612 and is shown in Figure 1.

Figure 1. CPA 0612 Current Simulation

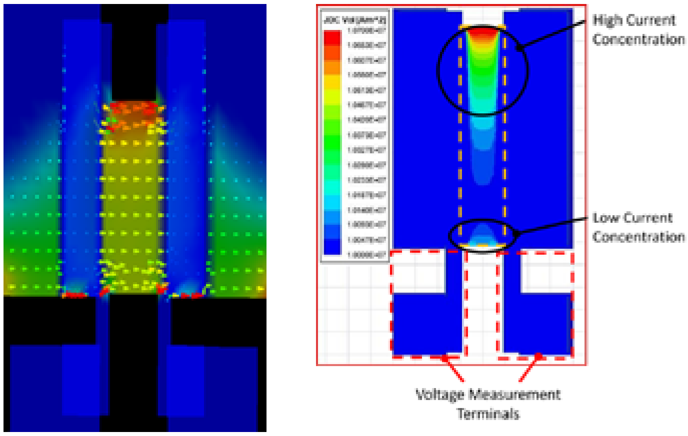
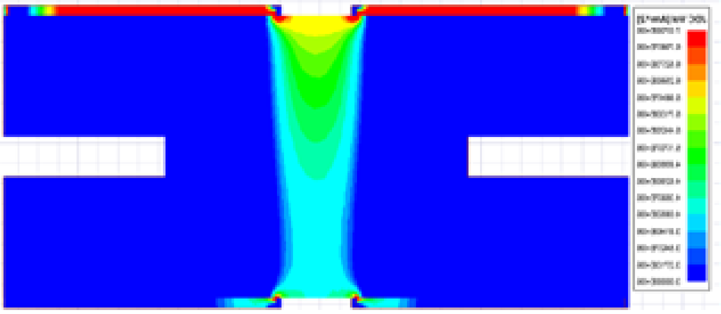


Figure 2. WRL 1206 Current Density Simulation



It can be seen from Figure 1 that most of the current is concentrated in the top region of the resistive element, while less current is concentrated near the voltage measurement terminals. When measuring the resistance, the measured voltage is divided by the supplied current. As the current is not distributed evenly, the voltage measured will be less than the total voltage drop across the resistor.

When exposing the WRL resistors to the same test conditions as the CPA series, the WRL series proves to be far less prone to measurement inaccuracies. This can be explained by the WRL resistors unique design to limit current crowding effects, resulting in consistent measurements for various uses. The distribution of current in the WRL part is shown in Figure 2.

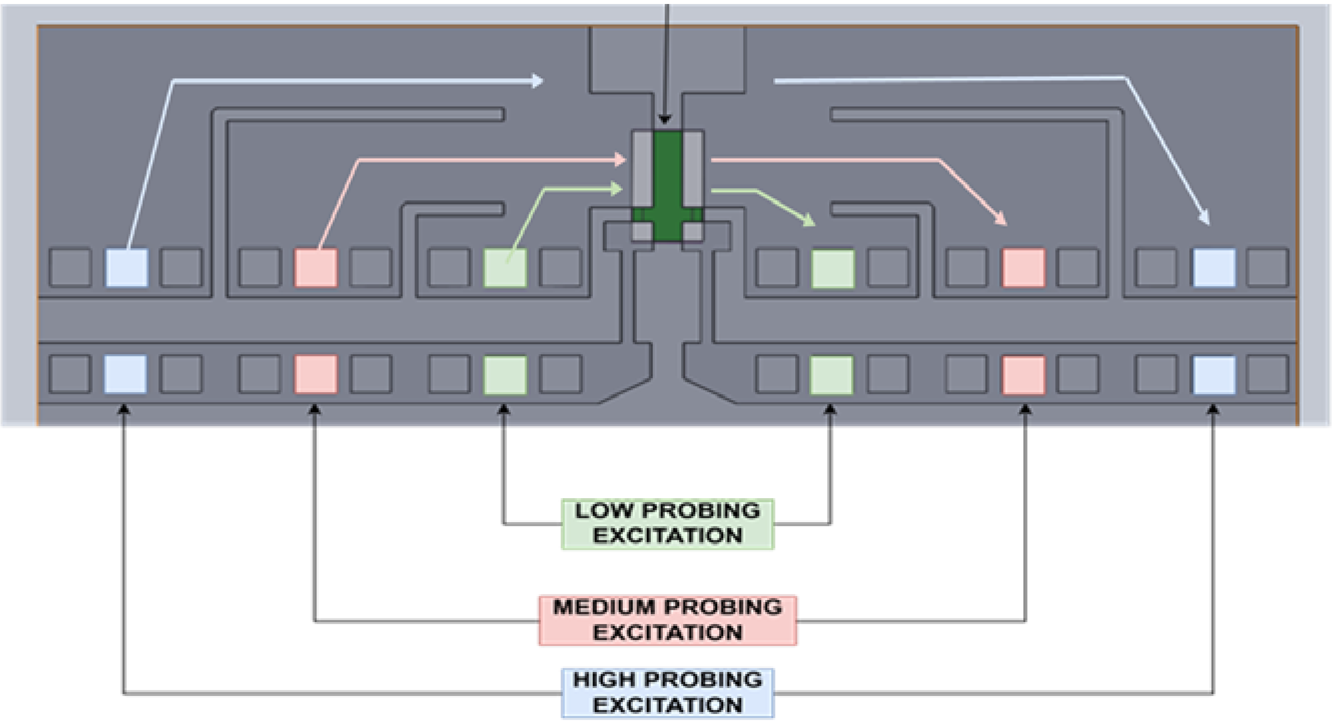
The resistance measurement of the CPA 0612 resistors may vary due to installation accuracies and PCB design. Variation in measurements can be decreased by increasing the thickness of the PCB copper, ensuring the part is properly aligned when installing, and ensuring that current excitation locations allow for uniform current flow.

Current Crowding Effects on Ultra Low Ohm Current Sense Resistors

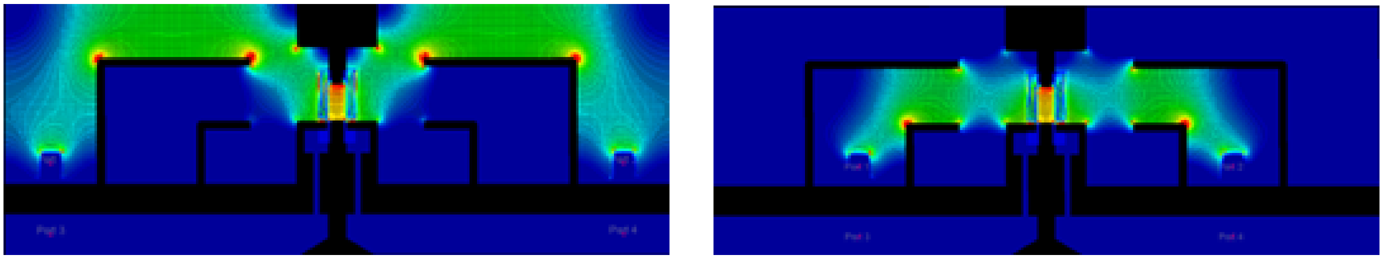
Thin Film Technology Corp's CPA 0612 series is a low ohm, metal foil, current sense resistor. This resistor features a 4-terminal design with Kelvin connections to minimize the effects of contact resistance and achieve tighter tolerances. When independent engineers measured the resistance of the CPA, a discrepancy of 2-3% was found comparing to measurements conducted inhouse. It was observed that the test board design was not in full compliance with the TFT recommended land pattern. Resulting discussions with independent engineers lead TFT to theorize that this could lead to current crowding errors. The specific parameters that would be expected to contribute to current crowding within the CPA include; the excitation location, resistor misalignment, thickness of the PCB's top layer of copper, and coplanarity. A specialty test board was then designed to measure the CPA's resistance while varying the excitation location, resistor misalignment, and PCB copper thicknesses.

The excitation location of current flow refers to the point at which current is applied and voltage is measured on the test board. Figure 3 below illustrates the CPA resistor mounted on the test board with three different excitation locations, denoted as low excitation, middle excitation, and high excitation. The arrows in Figure 3(a) represent the flow of current for a given excitation location. Figures 3 (b-d) show current density simulations for the different excitations to help visualize the path of current.

Figure 3. CPA Test Board Exciation Locations

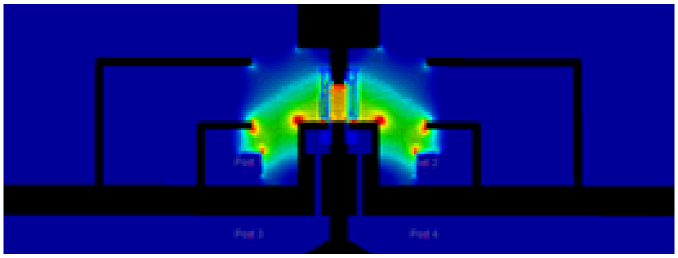


(a) CPA Part on Test Board with Exciation Locations



(b) High Excitation Simulation

(c) Middle Excitation Simulation



(d) Low Excitation Simulation

Figure 4. Misalignment Conditions

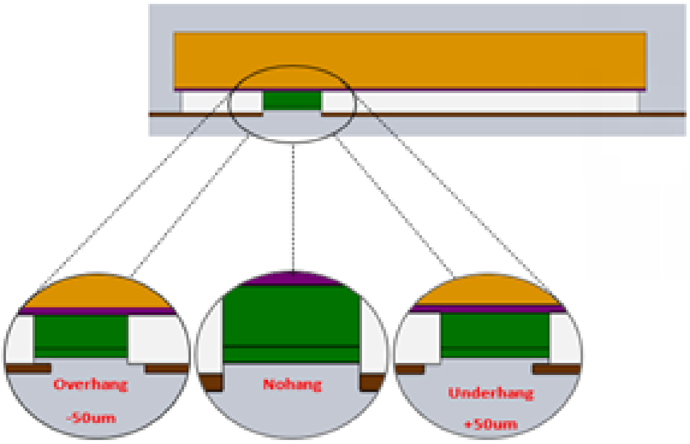
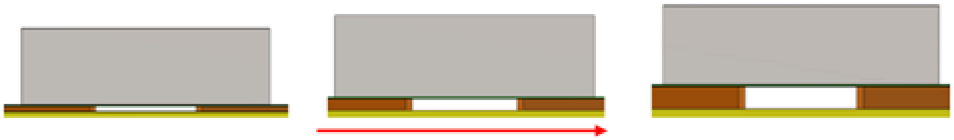


Figure 4 above depicts the resistor misalignment condition, which refers to the length of misalignment when the resistor's electrodes are soldered to the PCB land pattern. The test board can test three misalignment conditions, denoted overhang, nohang, and underhang. Overhang and underhang refer to $-50\ \mu m$ and $+50\ \mu m$ misalignments, respectively, while nohang refers to no misalignment. This misalignment results in an uneven contact surface between the PCB and the part, potentially creating unwanted concentration of current that can cause the measured resistance to drift.

Figure 5. Increasing Top Layer PCB Copper Thickness



The copper thickness of the top layer of the PCB, shown in Figure 5, could also impact the CPA's resistance variation. Less copper may not provide enough space for the current to spread evenly, resulting in current crowding. The test boards were designed with three different thicknesses of copper, 0.5 oz, 1.0 oz, and 2.0 oz.

Various experiments and simulations, considering the possible combinations of effects previously described, were conducted on a CPA0612DR001FT-T50 part manufactured to a nominal resistance value of $1\ m\Omega$. Table 1 below compares variations in measured resistance between using high vs low excitation, presence of the overhang condition vs no overhang, and increasing PCB copper thickness.

Table 1. Measured Resistance Variation in CPA0612 Resistor for Different PCB Thickness

Copper Thickness [oz]	Simulation		Experimentation	
	Excitation Variation (High-Low)	Overhang Variation	Excitation Variation (High-Low)	Overhang Variation
0.5	5.3%	1.6%	4.7%	0.5%
1.0	3.4%	1.3%	3.2%	0.9%
2.0	1.8%	1.0%	2.3%	0.2%

The measured resistance of the CPA part can be seen to vary when using high vs low excitation as well as when the overhang condition is present, as verified through simulation and experimentation. Increasing the copper thickness of the PCB connections appears to reduce these effects, as the percent variation decreases as copper thickness increases.

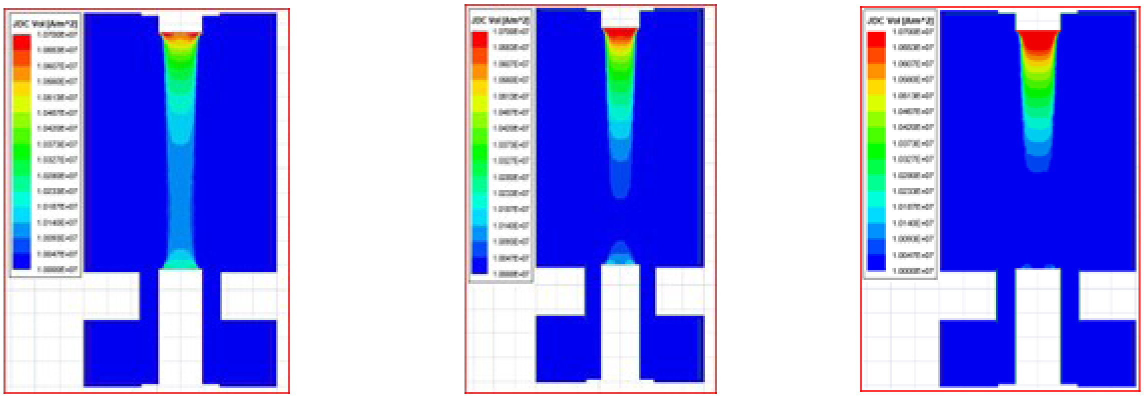
These results motivated TFT to develop a new current sense resistor, the WRL1206, to eliminate the variations in resistance due to current crowding. The WRL's design forces the current to enter and exit at the same location, regardless of excitation location and uses copper to spread current evenly through the resistor. To verify the design's effectiveness, the same study is conducted on the WRL as was done with the CPA using similar test boards. The results of the study are shown below in Table 2.

Table 2. Measured Resistance Variation in WRL0612 Resistor for Different PCB Thickness

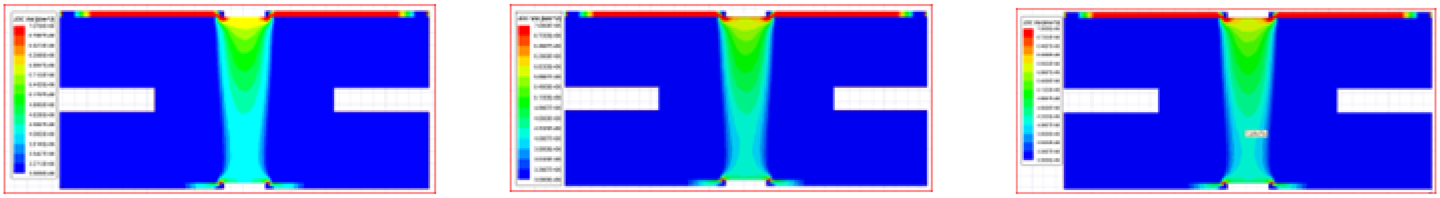
Copper Thickness [oz]	Simulation		Experimentation	
	Excitation Variation (High-Low)	Overhang Variation	Excitation Variation (High-Low)	Overhang Variation
0.5	0.01%	0.6%	0.003%	0.124%
1.0	0.01%	0.6%	0.004%	0.044%
2.0	0.01%	0.6%	0.004%	0.044%

It can be observed that the WRL resistance does not experience notable variation when subjected to the same conditions. The variation in resistance remains minimal and almost constant under different test conditions. In other words, the WRL resistor design eliminates tolerances due to design for manufacturing. Figure 6 below shows current concentration simulations from both a CPA and a WRL simulation subjected to the same conditions.

Figure 6. CPA (a-c) and WRL (d-f) Current Density Simulations



(a) CPA Low Excitation (b) CPA Middle Excitation (b) CPA High Excitation



(a) WRL Low Excitation (a) WRL Middle Excitation (a) WRL High Excitation

From Figure 6, it can be clearly seen that the current distribution remains constant within the WRL, while current crowding effects can be seen within the CPA. This supports the theory that variation in resistance measurements for the CPA is due to current crowding.

It is observed that different test conditions and PCB designs can affect the measured resistance for the CPA0612 current sense resistor. The WRL1206 is designed to reduce these effects when analyzed alongside the CPA resistor for a base of comparison. The WRL design is proven, as the measured resistance remains near constant under the same conditions that the CPA was subjected to. Comparing the two parts' simulations further suggest that the variation in the CPA's resistance is likely a result of current crowding. More parameters that may affect measured resistance, such as coplanarity, will be investigated in a future study.

In conclusion, both CPA and WRL provide accurate measurements when properly mounted to a PCB and thus have their uses depending on a project's need. It is advisable to contact sales@thin-film.com or visit TFT's website for consultation on which of TFT's products best suit your design.