Maskless Printing of Miniature Polymer Thick Film Resistors for Embedded Applications.

Jason A. Paulsen and Michael J. Renn

Optomec, Inc.

Saint Paul, MN 55114

Abstract

Applications for embedded polymer thick-film (PTF) resistors continue to grow in number, especially in the area of flexible substrates. With the ever increasing complexity of new applications, more advanced processes need to be developed in order to keep up with size, cost, and throughput constraints. We are developing a new printing method, known as M^3D^{TM}, for depositing high precision PTF resistors. This new approach produces resistors with a variability of better than 10 % in the range of 100 Ω – 10 kΩ and at a footprint below 0.05mm^2. The process involves aerosolizing a PTF paste material and then forming an aerodynamically focused jet of the paste droplets. The droplet stream is deposited at specific locations on a PCB through CAD/CAM control. The CAD/CAM control allows the locations and resistance values to be determined from the CAD file, which eliminates the need for creating screens or stencils and eliminates trimming requirements. The aerodynamic jet can be focused down to 25 microns which allows smaller geometries to be printed than is possible with existing methods. We will report on test runs of over 900 resistors of multiple values which yielded >87% of resistors within 7% tolerance from a target resistance value and 98% within 10% of the target value. Since M^3D^{TM} is a CAD driven process, the initial setup costs are lower and design cycle times are reduced. This makes M^3D^{TM} a cost-effective solution for printing embedded resistors.

Introduction

To enable the printing of high tolerance resistors with a small footprint a technology called "Maskless Mesoscale Materials Deposition" (M^3D) from Optomec Design Company was utilized[1,2]. M^3D, shown schematically in Figure 1, is a non-contact printing technique involving the aerosolization of a starting fluid or ink with a modified Collison nebulizer[3]. This aerosol consists of droplets approximately 1-3 microns in diameter. After some inline conditioning of the aerosolized material, it is fed into a focusing head that directs it into a particle stream with a diameter as small as 10 microns. The focused particle stream exits the deposition head at velocities of approximately 100m/s, with a volumetric output as high as 0.25mm^3/second, and standoff distance from the substrate of 5mm. The location of the deposited ink is determined by translating substrates under the deposition head with CAD/CAM control. This enables real-time changes in the toolpath to be made.

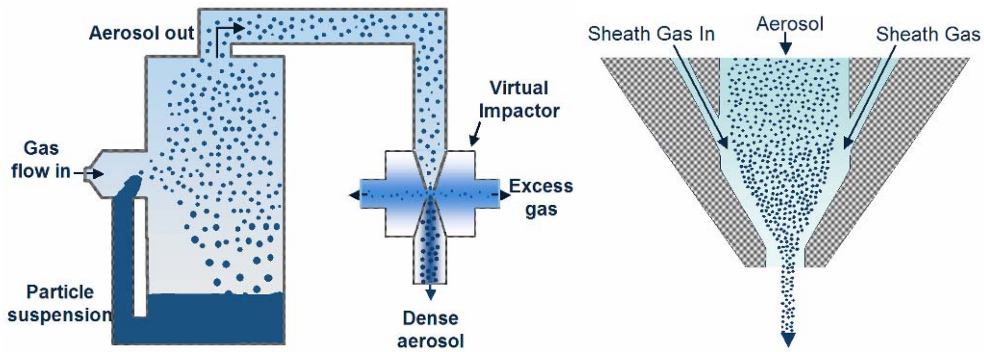

Figure 1 – Schematic diagram of the M^{3}D^{TM} deposition process. Liquid PTF ink is first nebulized (left) to form a cloud of 1-3 micron-sized droplets. Excess carrier gas is removed with a virtual impactor. The droplets are directed to a focusing head (right) where a sheath gas collimates the droplets into a high-velocity, small-diameter, particle stream. The printing is accomplished by translating the substrate under the deposition head.

Because of the very small size of the droplets and the CAD driven patterning process, the M^{3}D process has many differences from conventional techniques. This process allows very accurate volumetric depositions with a high level of geometrical accuracy. With this accuracy, the deposition system can be tuned to deposit an exact amount of material to print resistors with a specific resistance values at specified locations. Because of the CAD control, the process can be fine tuned in real time by adjusting the deposition parameters of the tool to compensate for any process drift. These unique features allow a wide range of resistance values to be deposited with a single paste on a single board. Since this is a single printing step, the laser trimming step required by other conventional process is eliminated.

Experimental Methods

The geometric dimensions of a single material resistor predominately determines the value of a printed resistor[4]. A benefit of M^{3}D^{TM} process is the ability to control the thickness and width of a printed resistor easily by adjusting the deposition parameters. The thickness of the resistor can be controlled by the number of layers of material deposited, the tool speed of the process, and the volumetric deposition rate. The width of the deposited resistor is adjustable with adjustments to the CAD/CAM control. Figure 2 shows a schematic diagram of a typical toolpath for depositing resistors. The tool is rasterd back and forth to deposit ink between two metal pads. The raster spacing is an adjustable feature and adjacent rasters are typically set to overlap slightly to allow a smoother surface finish. The width of the resistor is determined by the number of rasters and the raster spacing. The volumetric deposition rate of the head is typically held constant, but the speed of the tool can also be adjusted for fine control over the amount of material being deposited at any given location. This typically is used to control the thickness of the deposited feature and can be used to fine tune the total volume of material being deposited. The M^{3}D process is capable of producing resistors with widths as narrow as 50um, lengths as short as 100um, and thicknesses up to 50um.

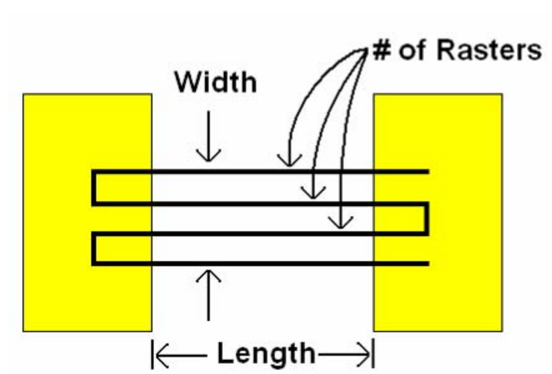

Figure2: Schematic diagram of a toolpath for printing PTF resistors. The primary variables are the length, spacing of the raster lines, number of raster lines, and the number of layers.

This study focused on printing an off-the-shelf carbon resistor paste (Asahi TU-15-8) that had a nominal sheet resistance of 15 Ohms/sq. Due to the high viscosity of this paste, it needed to be diluted to allow more efficient nebulization in the M3D process. The as-received ink was diluted by 33 wt% with Diethylene Glycol Dibutyl Ether. This allowed the ink to be deposited with smooth surface finish features, as can be seen in Figure 3.

To develop the printing technique and evaluate resistor performance, a custom printed circuit board was fabricated which contained 72 pairs of conductive gold pads on BT circuit board. The 72 locations were divided up into 12 sets of six with each set having 12 gap lengths from 0.1mm up to 1.2mm in increments of 0.1mm. After depositing resistor ink, the boards were cured in a reflow oven according the manufacturers specifications (170C @10mins). Two-point, resistance values were measured with a hand-held Fluke multi-meter and evaluated with respect to deviation from mean value and from specified target value.

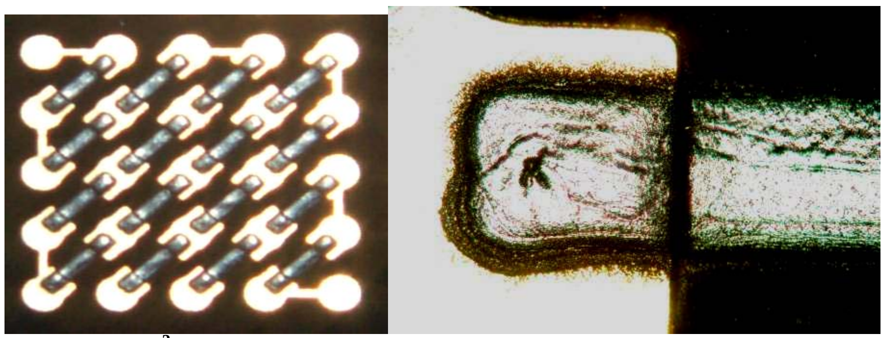

Figure 3 – Micrograph of M^{3}D deposited resistors. a) test resistors between pads with a spacing of 800um and resistor width of 175um b) Micrograph of resistor showing the surface finish quality

Control of Resistor Geometry

Various resistor geometries were printed in order to investigate the statistical variance of resistance values as a function of geometry. The parameters studied are resistor length, number of rasters (R), number of layers (L), and raster spacing (S). The deposition speed was held constant at 3mm/sec for this test. Figure 4 shows the values of resistors printed with various geometrical combinations. Each data point on this plot represents the average of 30 individual resistor values. As can be seen, the resistance value depends linearly on length. Figure 5 shows the values of resistors printed with respect to the width. The resistances decrease monotonically with increasing width as would be expected.

The deviation of the printed resistors with respect to the average value for each data point in Figure 4 is calculated and listed in Table 1. It was found that certain resistor geometries produced significantly less variation from the mean than others. In general it can be seen that resistors longer then 0.6mm tend to have lower variation then resistors shorter then 0.6mm. Specifically, resistors with lengths of 0.1mm have double digit variation regardless of width and thickness. These lengths may not be suitable for printing high tolerance resistors without further optimization. It can also be seen that three or more layers should be printed to reduce the variation below 5%. Raster spacing of up to 70 um were explored in this trial but no strong dependence was found. Qualitatively it was found that the raster spacing should be set to give approximately 30% overlap of printed lines. If the overlap is not sufficient, the surface morphology will show dips in the overlap region and the variance will increase. Figure 5 shows the correlation between resistor width and measured resistance value. This curve does not scale inversely with width because the overlap between adjacent raster lines causes the resistors to print thicker as well as wider. The data from this test can be used to determine preferable geometries for printing high tolerance resistors.

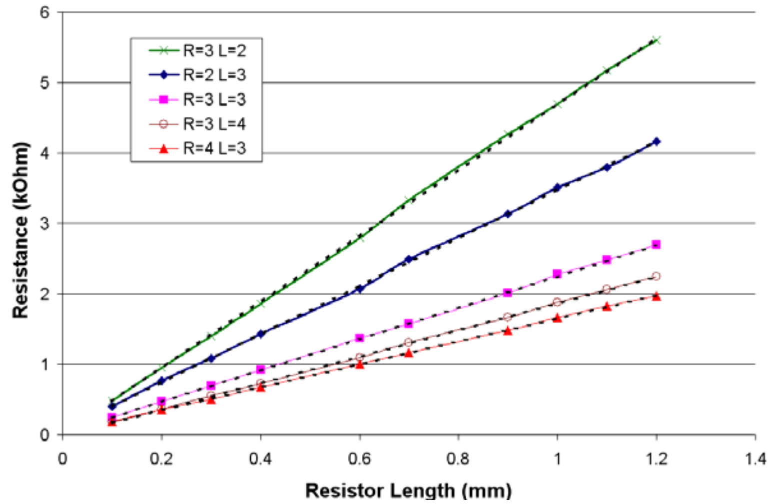

Figure 4: Resistance of M^3D generated resistors for various deposition geometries. The legend symbols are as follows: R = # of rasters, L = # of layers

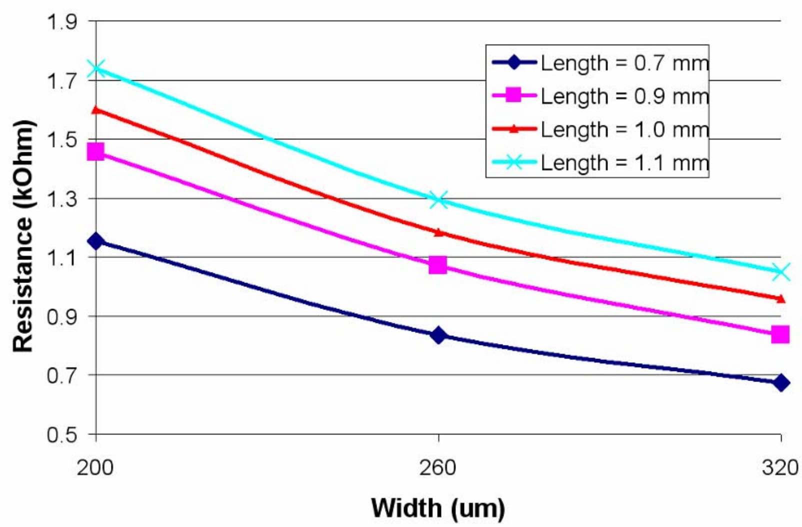

Figure 5 – Dependence of resistance value on width of resistor for various length. The dependence is inversely proportional to width because of the overlapping raster lines change the thickness as well as the width.

Table 1 – Percentage variation of resistor value from average value for various combinations of length, width, and thickness. The variance generally increases as the width and length decreases

Speed=3 Layers=3										
	Length (mm)									
Width	**0.1**	**0.2**	**0.3**	**0.4**	**0.6**	**0.7**	**0.9**	**1**	**1.1**	**1.2**
150 um	16.9%	5.7%	5.8%	7.0%	6.5%	6.4%	6.3%	7.0%	7.0%	5.9%
220 um	12.9%	5.3%	4.1%	7.1%	3.4%	4.2%	4.8%	5.5%	4.4%	5.3%
290 um	7.5%	4.9%	6.0%	5.4%	4.6%	8.9%	4.8%	4.5%	5.8%	2.8%

Speed=3 Rasters=3										
	Length (mm)									
	0.1	0.2	0.3	0.4	0.6	0.7	0.9	1	1.1	1.2
2 Layers	11.0%	7.9%	10.5%	5.2%	5.7%	4.6%	6.7%	4.7%	4.1%	4.4%
3 Layers	9.5%	6.5%	4.1%	3.3%	1.7%	4.5%	3.3%	2.4%	3.9%	2.8%
4 Layers	6.2%	4.9%	3.9%	4.3%	2.6%	2.7%	3.7%	2.1%	4.4%	3.2%

Temperature Effects

In addition to geometrical shape of the resistor, the resistance value is strongly affected by the ambient temperature of the ink. This dependence is attributed to viscosity changes in the ink which can greatly affect mist generation of the Collison nebulizer. The nebulizer is observed to cool down by as much as 6°C during operation due to evaporative cooling of the ink. The majority of the cooling occurs within the first few minutes of startup but it depends on the specific flow rates in the nebulizer. Consequently the flow and deposition rate is held constant during the printing process. Because of the importance of temperature fluctuations, the effect was studied quantitatively. Figure 6 shows the dependence of resistor value on ink temperature. As seen, a linear correlation is found between the temperature of the atomizer and the final resistance values. The slope of the curve indicates a value change of approximately 10% per 1°C change in ink temperature. This implies that the temperature of the atomizer needs to be held to within ± 0.1°C in order to hold systematic drift to below 1%. The current M3D lab system used a temperature controlled water bath to stabilize the ink temperature to this level.

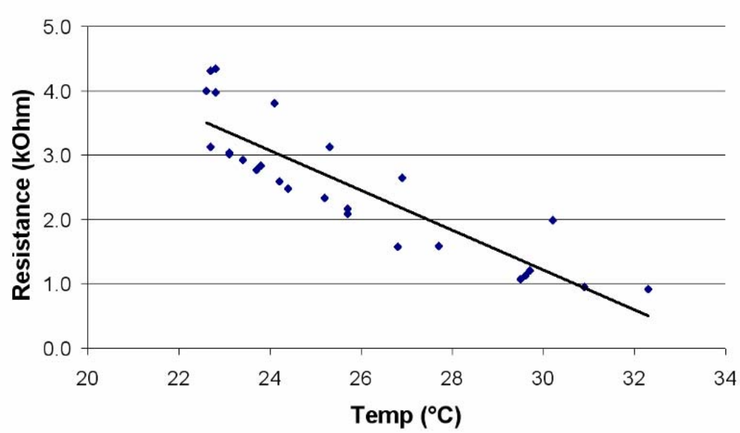

Figure 6 – Graph showing the effects of nebulizer temperature on the resistance of M^{3}D printed resistors. The temperature was scanned by initially applying heat to the ink container and then allowing it to return to ambient. The linear correlation between nebulizer temperature and resistance values gives a rate dependence of approximately 10% change per degree.

Calibration Process

The previous sections have described the primary variables effecting resistance value and sources of systematic drift, namely geometrical shape and ink temperature. In order to print resistors to a specified tolerance these variables need to be controllable and adjustable. There are several possible methods for printing precision resistors. The most straightforward is to optimize the system for constant deposition rate, namely by controlling temperature, and flow rates, and then adjust resistance value through the toolpath namely, width, length, and thickness. The geometrical changes are easily and quickly changed through the toolpath.

The first step to printing a precision resistor is to correlate the resistor values with specific geometries. In this step, an array of resistor geometries are printed on a test board and the discrete values recorded. These values are then compared against desired target values to find the specific geometry that most closely matches the target value. As an example of this calibration procedure, we present a calibration procedure for printing four specific target values, namely 0.7kΩ, 1.5 kΩ, 1.2 kΩ, and 1.7 kΩ. Table 2 shows the matrix of resistor length and width. The geometrical combinations that most closely match the target resistance value are highlighted. The matrix size can be adjusted to accommodate various numbers of target resistors or larger value ranges.

Table 2 – Resistance values for the initial calibration step are shown here. The target resistances are 0.7 kΩ, 1.5 kΩ, 1.2 kΩ, and 1.7 kΩ. The number of rasters used to create resistors with each target value were chosen from this information by selecting the number of rasters which generated a resistance closest to the target value.

		Length (mm) **0.7**	 **0.9**	 **1**	 **1.1**
# of Rasters (width)	**3 (200um)**	1.155	***1.45***	1.60	***1.74***
	4 (260um)	0.835	1.07	***1.18***	1.2
	5 (320um)	***0.674***	0.83	0.95	1.05
Target		0.7 kΩ	1.5 kΩ	1.2 kΩ	1.7 kΩ

The second step in the calibration procedure is to fine-tune the resistor thickness to zero in on the target values. Since the deposition rate is held constant throughout the process, the most effective way to adjust thickness is to vary the translation speed of the substrate. More material is deposited when the substrate is translated slower and vice versus. An array of resistors of the specific length and width from step one are printed but with variable print speed. Figure 7 shows the dependence on print speed. As can be seen the curves span the desired target values. By linearly interpolating the curves, the exact tool speed can be determined to accurately print a specific target resistance. In this example the 0.7 kΩ resistance will require a tool speed of 3.152mm/sec. Similarly, the 1.5 kΩ value is achieved with a speed of 3.148mm/sec, the 1.2 kΩ value with a speed of 3.037mm/sec and 1.7 kΩ with a speed of 2.950mm/sec. This concludes the calibration procedure. Resistors printed immediately following the procedure will yield resistances very close to the target value.

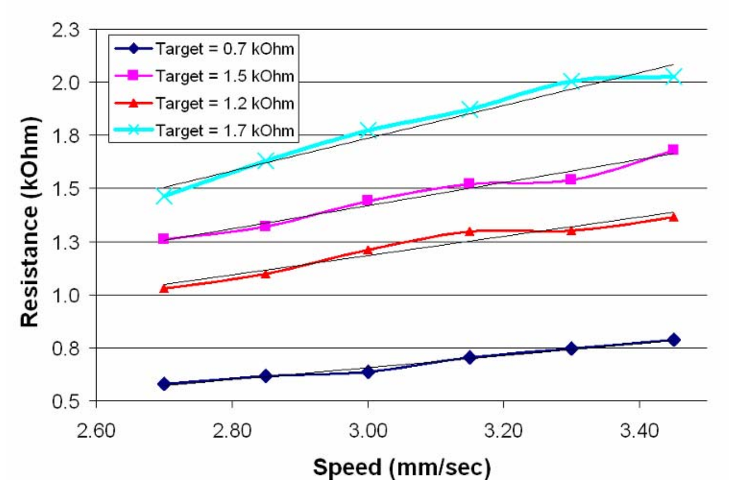

Figure 7 – Plot of the fine tuning calibration step showing the linear trend of the resulting resistance with respect the tool speed. The specific tool speed required to generate a specific resistance value can be determined from this information.

Results

Two studies were performed to evaluate the short and long term stability of targeted resistor printing. In the first test a set of 324 resistors with two target values were printed. The values chosen were 1.8kΩ and 3.2 kΩ. The calibration procedure described above was performed before printing the resistors. The resistors were then printed over a period of two hours. Figure 8 shows the measured values of these 324 resistors. As can be seen, the measured resistances are very close the target value. A gradual drift downward in value of approximately 3% is observed. We believe this is cause by residual thermal drift in the atomizer.

Figure 9 shows a graph of the deviation from the target value. The slight downward drift is evident in this plot as well. Despite this, 91.6% of the resistors deposited were within 5% of the target value and 100% are within 7%. This shows very good short term stability in the system.

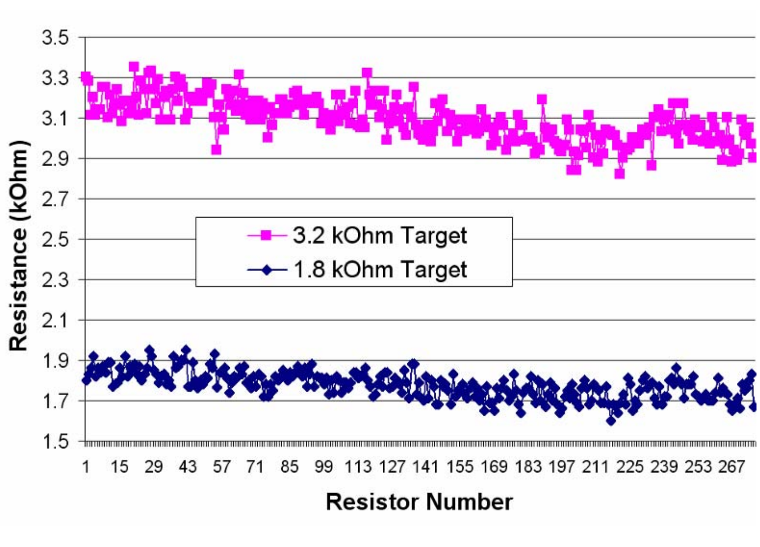

Figure 8 – Results from an initial study to evaluate the short term stability of the printing process for targeted resistors.

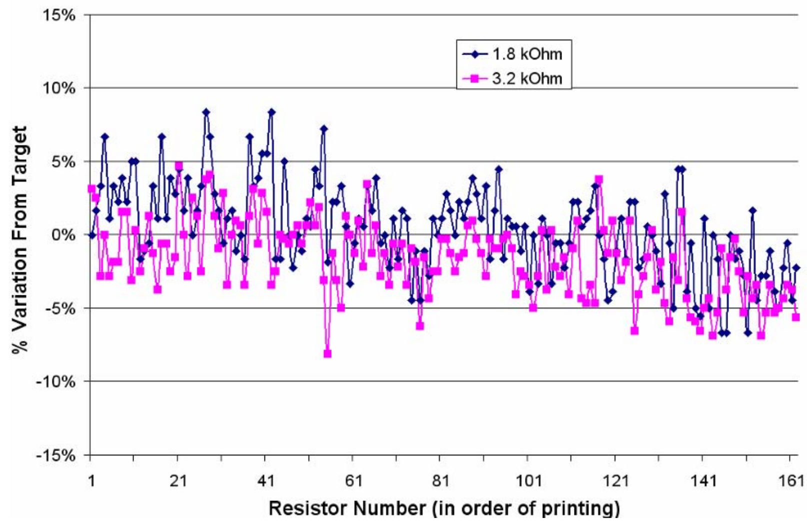

Figure 9 – Data from Figure 6 plotted with respect to deviation form target value. Note that 100% of the resistors are within 7% of the target value, which indicates good short term stability in the system.

A more extensive test with multiple target values and a two day run time was carried out evaluate the long term stability. This test involved depositing more than 960 resistors with four targeted values on 40 separate boards. Data showing the measured deviation from the targeted value is shown in figure 10. As can be seen the measured values are generally within 10% of target, except for a few anomalies. The source of anomalies is not clear, but we speculate that board cleanliness may be a issue as the printing was not performed in a clean room. Also apparent in the data is a cyclic fluctuation of the measured values. This fluctuation can be traced back to oscillations in the ink temperature. It was discovered that the temperature of the ink was fluctuating by about ±0.3°C which causes a change in resistance by approximately ±3%. Despite this drift, >98% of the resistors are within 10% of the target value and >87% are within 7% of the target.

To separate the systematic temperature drift from the intrinsic process fluctuation, figure 11 shows the data plotted relative to a moving average. The moving average method calculates the resistor variation with respect to the average resistance of the specific board the resistor was printed on. Each board contains 6 resistors of each target value. This plot shows that the process fluctuations are below 7%. Table 3 lists the percent of the resistors within various tolerance ranges. If the thermal drift can be more accurately controlled, it is believed that 100% of the resistors will fall within 10% tolerance and 94% will be within 5%. Approximately 85% of the resistors have less then ±3.8% variation from the average value.

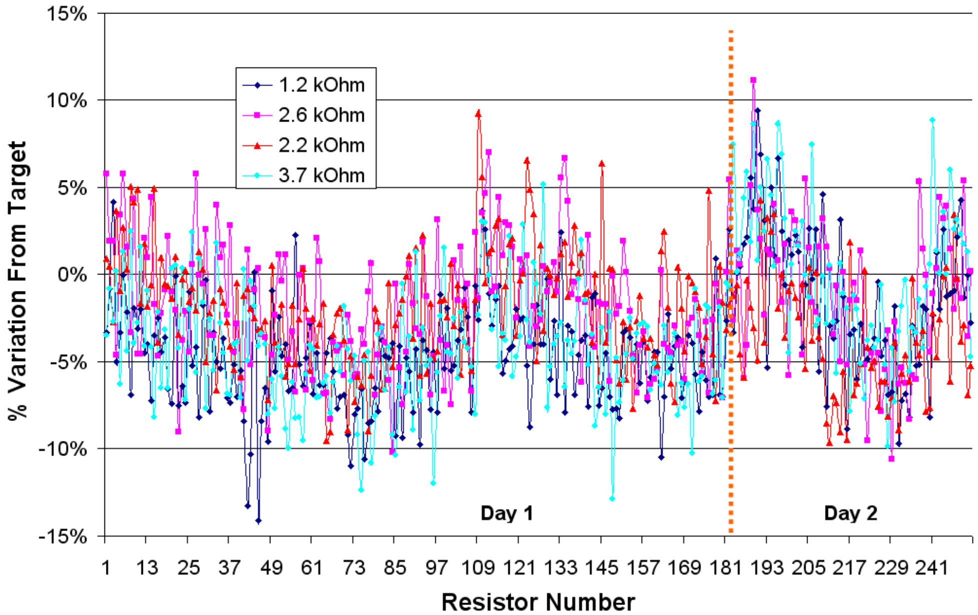

Figure 10 – Variation of the measured resistance with respect the target resistance for a test of 960 resistors. This test consisted of four target values on the same board and generated on two separate days.

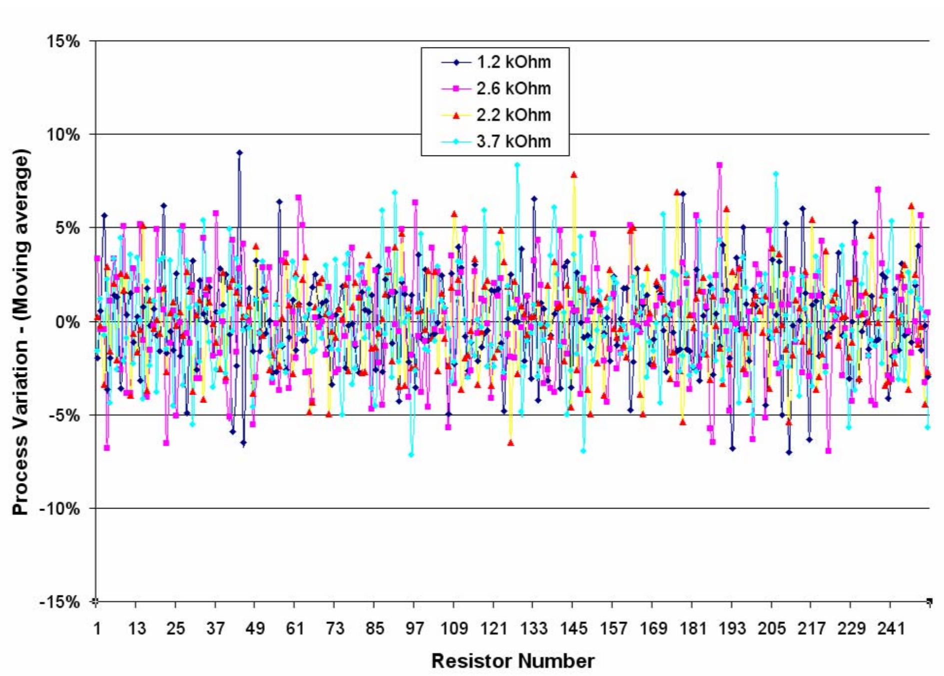

Figure 11 – Data from Figure 10 with compensation for systematic temperature drift. This plot indicates that the statistical variation for the printing process is approximately 7% over a multiple day run.

Table 3 – Tabulated results indicating the percentage of resistors falling within specified tolerance limits, after correcting for thermal drift. All resistor (100%) fall within 10% of the target and 91% fall with 5%.

		Resistor Length				
		0.7	**0.9**	**1**	**1.2**	**TOTAL**
Variation Limit	**10%**	100%	100%	100%	100%	**100%**
	5%	94%	91%	96%	94%	**94%**
	3%	80%	70%	78%	68%	**74%**
	2%	64%	51%	56%	52%	**56%**

Summery

An innovative printing process has been shown capable of printing high tolerance PTF resistors using off-the-shelf materials. The process is capable of printing multiple resistor targets on a PCB in a single step and without need for masks and trimming processes. A calibration procedure has been developed to determine the specific geometry needed for specified resistor value. The trials show that the system is capable of printing resistors over multiple days with a tolerance better that 10%. It is anticipated that improved control over ink temperature will further improve the tolerance to below 7%.

Although this work focused on evaluating a particular off-the-shelf ink, it is conceivable that other ink chemistries may produce better results. This needs further investigation. In particular, the temperature sensitive nature this ink is not a desirable property. From a process viewpoint, improvements can be made to provide a more stable and accurate process. Automating the calibration process could increase the stability of the system by allowing the fine-tuning calibration process to be performed more frequently to compensate for systematic drift.

Results here indicate a tolerance of approximately 7% is achievable with modest improvement to the temperature control. However it would be desirable to deduce this process variation to below 3%. This may be achievable by further investigating the effect of the known sources of the variations such as surface roughness and edge definition of the printed resistor along with the wetting properties of the ink onto the substrate and ink chemistry.

References:

[1]Pique, Alberto, Douglas B. Chrisey. *Direct-Write Technologies for Rapid Prototyping Applications*, Academic Press (2002) pp. 475-492

[2]Vanheusden, K., et al. *Direct Printing of Interconnect Materials for Organic Electronic*, Advancing Microelectronics 29, No. 1 (2002).

[3]May, K.R., *The Collison Nebulizer: Description, Performance and Application*. Aerosol Science, Vol 4, (1973) pp235-243

[4]Wang, G., Barlow, F., Elshabini, A., *Modeling and Control of Resistance Tolerance for Embedded Resistors in LTCC*, Electronic Components and Technology Conference (2002) pp. 516-525