ohmcraft WHITE PAPER

Photo Patterning Resistors

Tim Barge and Frank Collins

Abstract

Patterning thick film resistors with very fine lines enables the manufacturing of high value resistors with remarkable electrical performance. OhmCraft Inc has been co-optimizing material properties and design dimensions for many years.

The voltage coefficient of resistance (VCR) is inversely proportional to the length of the resistor. Serpentines of very fine lines enable increasing resistor length within a given area. Of course, the challenge is to manufacture narrow lines, which are uniform in width and thickness, with narrow white spaces.

In response to a customer request, OhmCraft, Inc manufactured a state of the art voltage divider. Using a proprietary fine line patterning process, we designed and built a ½ by 1 ½ inch, 1 Giga Ohm, 1000:1 voltage divider chip with 48.35 inches of serpentine. The VCR of the device is less than 1 ppm/V. The low side is trimmable to 0.25% ratio tolerance. The extraordinary length enabled us to use a thick film resistor ink with low intrinsic TCR, which also results in excellent TCR tracking. The device has 4 mil lines with 2 mil white spaces.

Using materials, tools and techniques of photolithography, and chemical etching, it is possible to manufacture thick film resistors with 1/2 mil line widths. Many of the available thick film resistor inks are compatible with this process. The very fine lines and broad range of resistor ink materials, enables design engineers to co-optimize resistors and networks for highly demanding custom applications.

Introduction

Thick film resistors have been manufactured since 1942. Ohmcraft began producing precision resistors using MicroPen direct writing in 1980. High voltage instrument and power supply manufacturers recognized the advantages and adopted the improved devices. As the business grew, so did requirements from customers. Ultra-precision resistors and networks not only improve the accuracy of their systems, but also reduce manufacturing costs and simplify repairs. This paper describes how to achieve maximum performance for resistors greater than 1 megohm.

Contemporary electronic circuitry often includes resistor components produced in the form of thin layers or films of conductive materials supported on an insulating substrate. Individual resistive elements of this type can be very small in size. Their manufacture, however, is generally done in the form of large repetitive two-dimensional arrays using wafer-scale processing techniques.

There are two distinct versions of film resistors. One version, referred to as thin film, is made using vacuum-deposited films of homogeneous materials a few hundred to a few thousand Angstroms in thickness. Different resistor values are achieved by forming these thin films into patterns having different length-to-width ratios, known as the aspect ratio. The patterning is done by photolithography. A layer of photosensitive polymer is deposited onto the resistive film. It is then exposed to a light source directed through a photo mask carrying an image of the desired pattern. The light renders the pattern in the polymer soluble by special solvents, thereby exposing the underlying resistive film in selected regions. The exposed resistive film is then removed using aggressive aqueous chemical agents or plasma etching.

The range of resistivity values available by changing the film material or its thickness is limited, to a factor of about ten, ranging from about 50 to 500 Ohms per square (the unit of which is the resistance across a pattern having an aspect ratio of one). Different values are, therefore, achieved primarily by varying the aspect ratio geometrically, using photolithography. Aspect ratios can be varied by a factor of many thousands, depending upon the minimum line width achievable and the chip area available.

Another common resistor manufacturing method is referred to as thick film. In this technology, a relatively limited range of geometrical patterns is employed and the primary way of varying the resistance value is achieved by changing the specific resistivity of the film material itself. These materials consist of a mixture of fine powders of glass and a conductive substance, typically ruthenium dioxide or ruthenate compounds. These powders are mixed with an organic vehicle to form a viscous ink. The ink is deposited onto an insulating substrate in patterns using stencil screen-printing techniques. After the volatile vehicle is removed in a low temperature oven, the system is raised to a higher temperature to fuse the glass constituent, resulting in a partially conducting glaze. The specific resistivity of the glaze depends upon the relative proportions of glass and conductive phase; the resistivity can range over a factor of ten or eleven decades. The thickness of the final film is about a half a mil.

For a given resistance value, resistive elements made from thin film are generally of higher quality than those of thick film. They have a smaller temperature coefficient of resistance (TCR), a lower current noise, a smaller voltage coefficient of resistance (VCR) and greater stability throughout service life. However, for a given size, thin film elements are limited in maximum value achievable compared with thick film elements. By using thick film compositions, with reduced conductive phase, resistors can be made in ohmic value several orders of magnitude higher than thin film.

While not generally as stable as thin film resistors, the quality of thick film resistors does vary significantly with value, that is, with composition. At very low values, where the proportion of glass phase is low, it has difficulty forming a continuous matrix and, therefore, cannot completely isolate the conductive phase from attack by atmospheric agents.

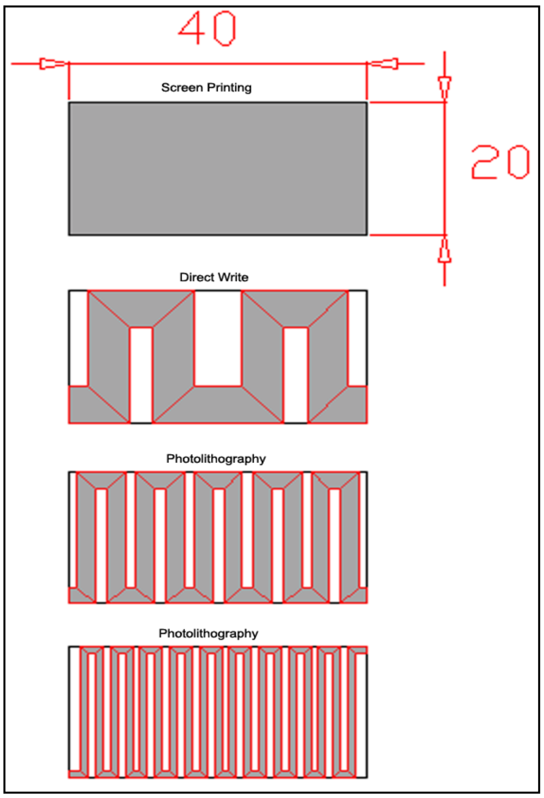
In mid-value compositions, the stability is improved. As the proportion of conductive phase is further reduced, to reach higher values, however, the quality degrades in relation to the degree of dilution of the conductive phase. The TCR is higher, the current noise is greater, the current-voltage linearity is poorer, and the service life is reduced.

One way of counteracting this tendency is to use thick film compositions of moderate specific resistivity and rely more on ways of achieving higher aspect ratios. As with thin films, the maximum aspect ratio achievable, within a given area, is a direct function of the minimum line width obtainable (it is inversely proportional to the square of the line width): The finer the line width, the higher the aspect ratio.

With conventional stencil screen techniques the minimum line width attainable is of the order of 10 mils. This would allow an element of 10 x 40 mils to be made by screen-printing with an aspect ratio of four.

An earlier idea, disclosed in patent # 5,521,576 is the discovery that higher aspect ratio patterns of thick film inks could be achieved using a quite different deposition technique,—namely the extrusion of ink through a small orifice in a capillary pen tip, much as in writing. By this method it was demonstrated that patterns based on line widths of 5.5 mils could easily be deposited directly onto substrates resulting in aspect ratios nearly an order of magnitude greater than could be produced by screen-printing. This means that in order to achieve a given resistance value, in a given size, an ink composition having nearly an order of magnitude lower resistivity could be used with a concomitant improved performance.

It has since been discovered that the photolithographic technique, ordinarily used with thin films, can be applied to thick resistive films, and that patterns designed with narrower line widths can be thereby generated, allowing compositions of even lower resistivity to be employed to reach a given value with substantial improvement in TCR, noise, and VCR performance. It has been found that line widths with thick film compositions down to 1/2 mil can be formed using photolithographic techniques enabling aspect ratios an order of magnitude higher than by direct write. A comparison of results obtainable by these different techniques is shown in the following table (figure 1), which shows how design affects the characteristics of a device which is 20 by 40 mils, and 1 gigaohm in value.



Line width	Aspect Ratio	Ink resistivity	TCR	VCR
mil		Ohm/Square	Ppm/C	Ppm/V
20	2	5.00E+08	300	-1270
5.5	17.8	5.62E+07	90	-39
2.5	86	1.16E+07	80	-15
1	401	2.49E+06	50	-5

Figure 1

Ink manufacturers provide families of ink which have members that have sheet resistances in steps of a factor of 10, that is 10, 100, 1000, 10^4 … Ohms/square. Normally, adjacent family members can be blended to achieve intermediate values. Inks with moderate sheet resistances, on the order of 1000 Ω/square, have the best intrinsic electrical characteristics. Their VCR, TCR, power handling, and noise are the best of the family. Optimizing electrical performance of high value resistors requires designs which utilize these preferred materials.

The following graphs display data taken from manufacturer's data sheets. The first letter of the label indicates the manufacturer, while the second letter indicates the family within that manufacturer. Note that the indicated TCR is a conservative figure. Appropriate firing conditions can reduce the TCR by a factor of ten from nominal.

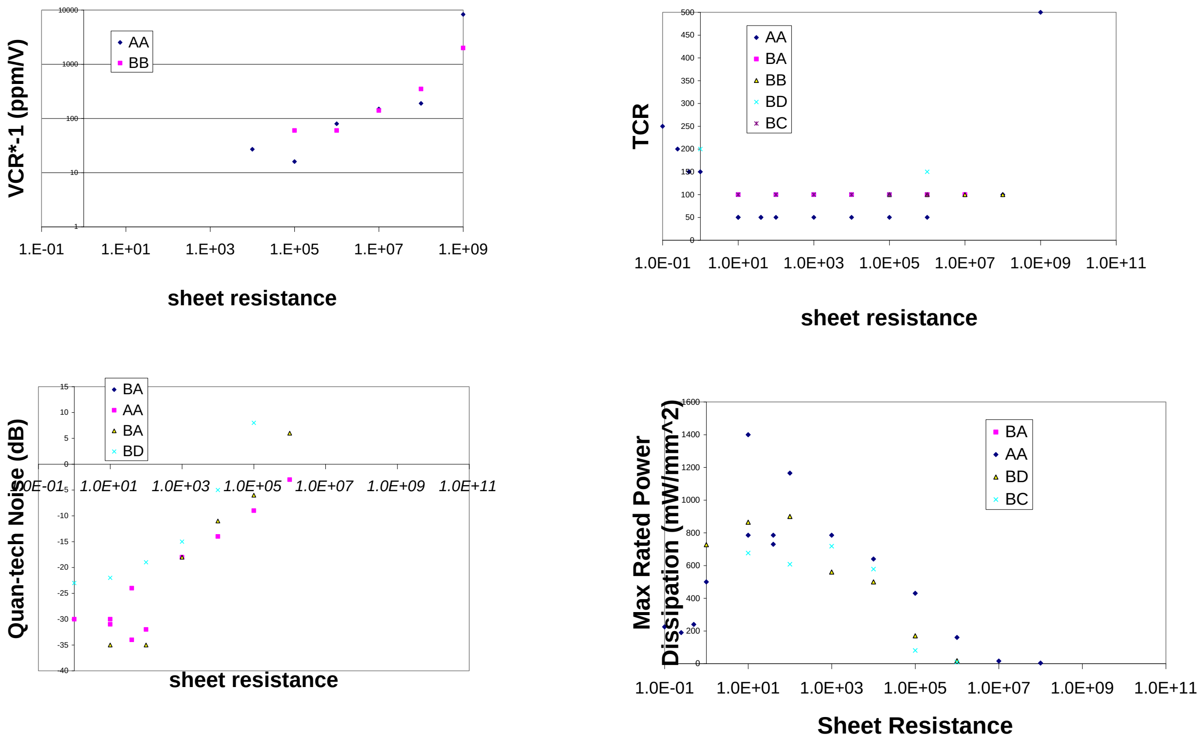


Figure 2

Taking advantage of the optimal material properties is as easy as making very fine lines.

Patterning Fine Line Thick Film Resistors by Photolithography

Making serpentine resistors with screen printing and direct writing processes can produce line widths of 4 mils, but their uniformity in width and thickness produce devices whose resistances vary about 5% within a plate. Using a photo patterning process, devices have been made with resistance variation of 1% and line widths of 1/2 mil.

Outline of method for photo patterned resistor fabrication:

1. Prepare substrate, preferably ground and polished 99.6% alumina
2. Apply uniform thickness of thick film resistor ink, typically by screen printing
3. Dry and fire the ink appropriately
4. Apply, dry, expose, bake and develop the photoresist image wise.
5. Etch the ink, using an appropriate etchant, such as Hydrofluoric Acid, accompanied by a directed stream of rinsing agent, such as deionized water.
6. Clean the etched plate with an appropriate surfactant, such as LiquiNox, to remove the residual powders.
7. Strip the resist using an appropriate stripping solution
8. Create electrical contact pads, using conventional thin or thick film techniques.

A Detailed Example

The following example was for an 875 MΩ 2510 (250 mils by 100 mils) chip with very low TCR, VCR, and trimmable to 0.5%. The photo patterned chips were laser trimmed to 0.5%, had TCR of less than 10 ppm/ ºC, and VCR of -2 ppm/V.

A 3.5 inch square 96% alumina substrate was screen printed with a large block of $1x10^6$ Ohm/square resistor ink. Screen printing is simplified by eliminating the constraints imposed by small apertures in the screen. The plate was fired in an 850 ºC, belt furnace for 30 minutes. The resulting thickness was 0.5 mils. The printed plate is shown in figure 3.

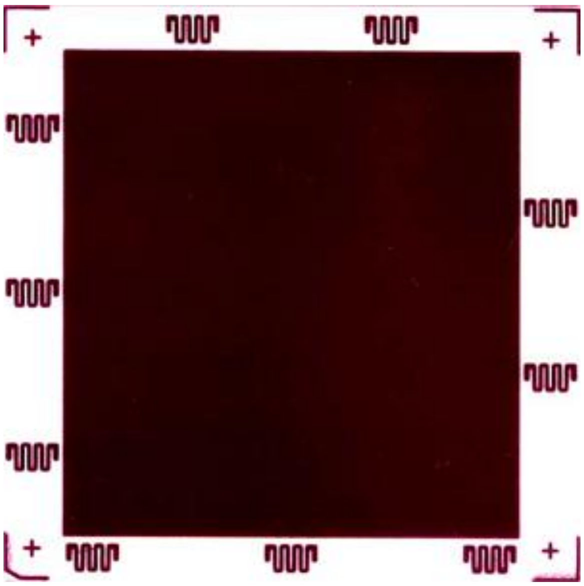


Figure 3

The plate was spin coated with a 1 micron thick layer of photo resist. It was soft baked 60 seconds at 90ºC. A polymer photo plot was used as a photo mask. The resist was exposed in an ABM Mask Aligner, 6 seconds at 65 mW/cm^2. The plate was post exposure baked 60 seconds at 90ºC, and developed. The plate was hard baked 4 minutes at 130ºC. Photo resist remained in the pattern of the desired resistor serpentine.

The plate was etched 60 seconds in an etchant comprised of 1 part HF, 1 part HNO_3 and 2 parts water. The plate was cleaned in a heated ultrasonic tank containing detergent, ultrasonically rinsed in water, and rinsed again. It was then dried.

The patterned plate is shown in figure 4.

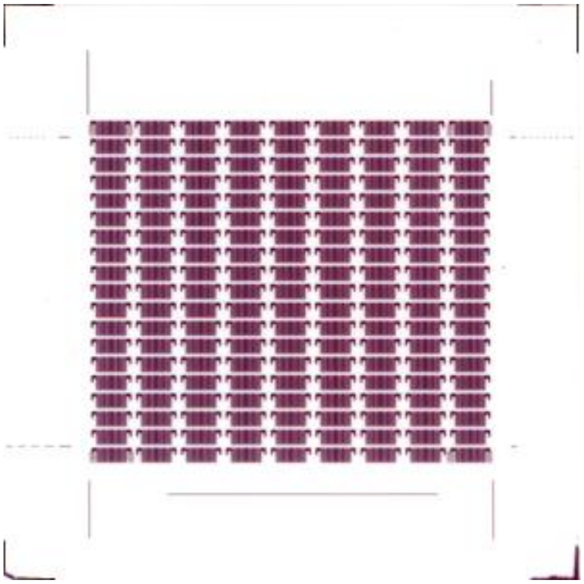


Figure 4

Then, the resistors were measured. If the value is less than desired, the plate can be etched additionally to achieve the desired aim.

Next, the photo resist is removed by immersion in stripper, followed by thorough rinsing, and drying.

Thick film conductor pads are screened and fired.

The remaining manufacturing steps are identical to chips made by other methods.

Figure 5 is a contour plot of one of the devices:

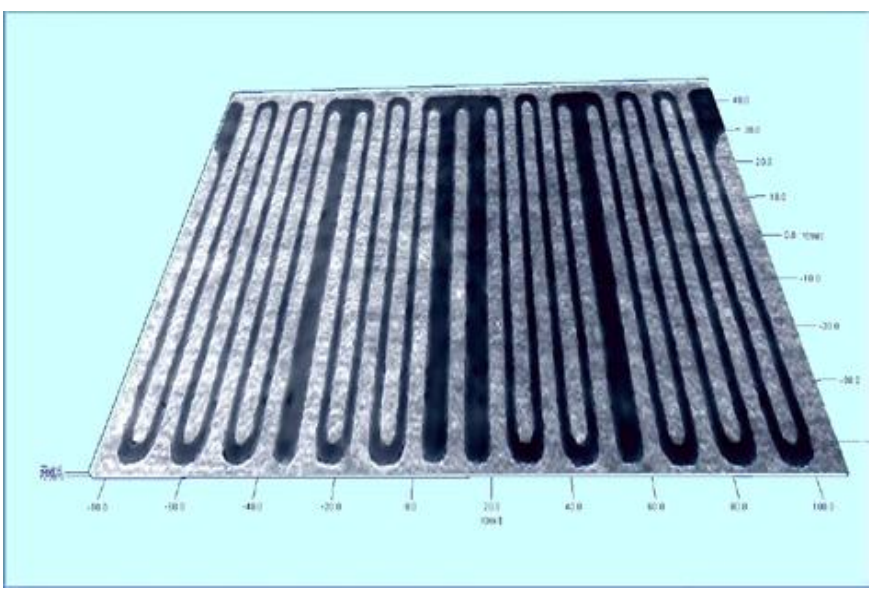


Figure 5

Figure 6 shows a contour plot of several of the lines:

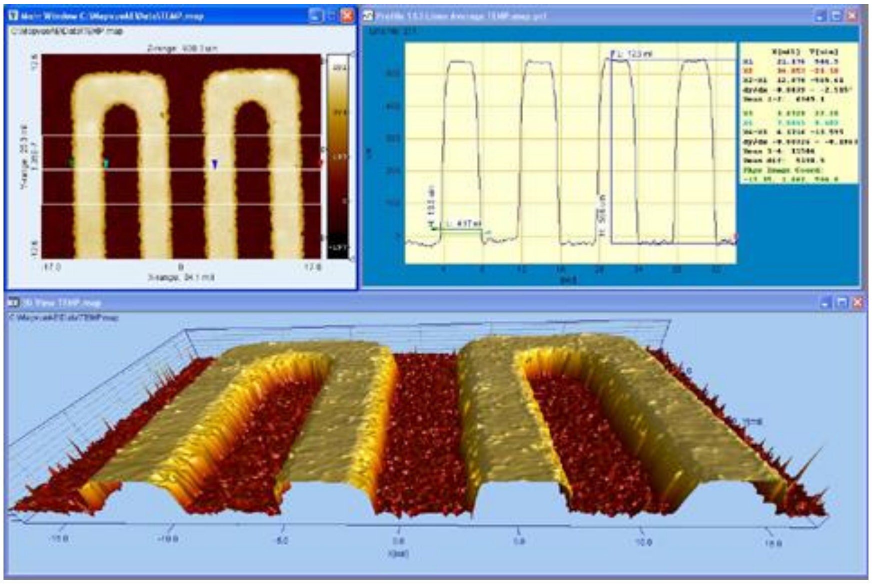


Figure 6

Comparison Examples

Figure 7 shows standard chip resistor of 40 x 30 mil in size (0403) was made using the direct-write technique, in a resistor value of 30 Gigaohm ($30x10^9$ Ohms), shown in figure 7. The nominal line width was 5.5 mils, and the aspect ratio 16 and the resistivity of the thick film was $2.0x10^9$ Ohms/Square. The finished part had a VCR of –2000ppm/V and a TCR of –550 ppm/°C.

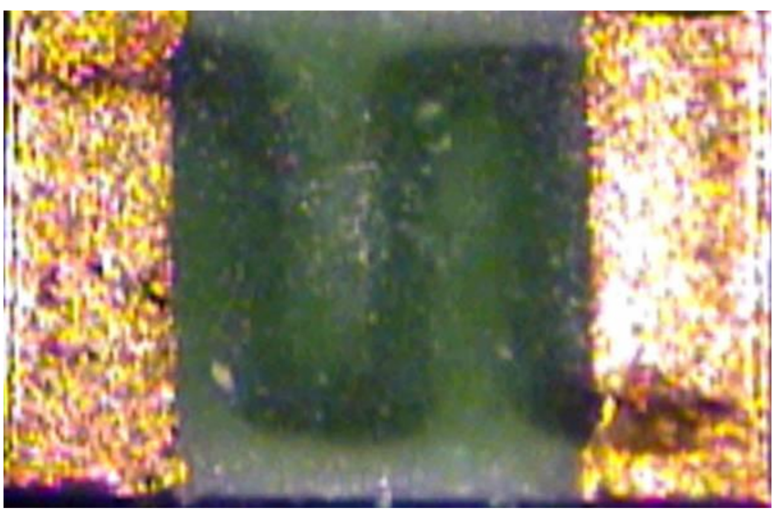


Figure 7

For comparison, figure 8 shows a chip resistor of the same size and resistance value, but with a line width of 2 mils and aspect ratio of 63 was patterned by photolithography, and is shown in figure 8. The resistive ink had a resistivity of $0.5x10^9$ Ohms/Square. The VCR was –550 ppm/V and the TCR was –200 ppm/°C.

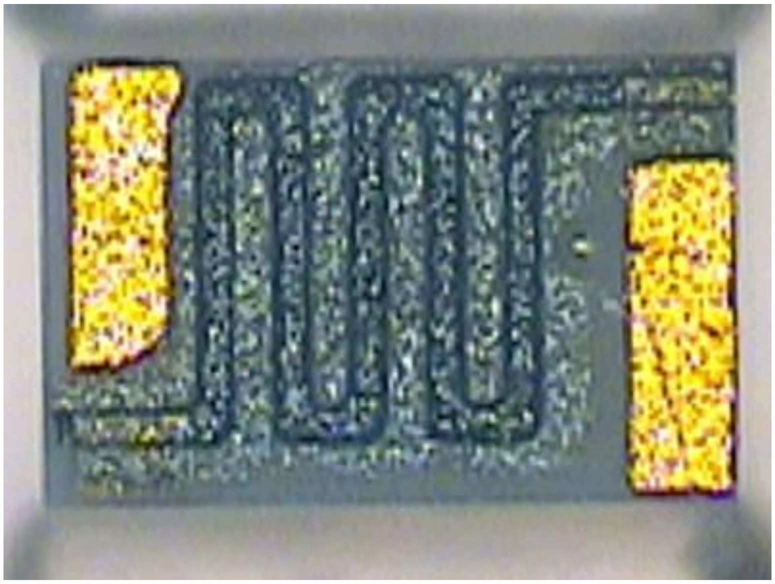


Figure 8

Another example of a resistor chip, which could not be made by screen printing and only with difficulty and poor yield by direct-write, was a chip 20 x 20 mils in size (0202) and 1 GΩ in value. This is shown in figure 9.

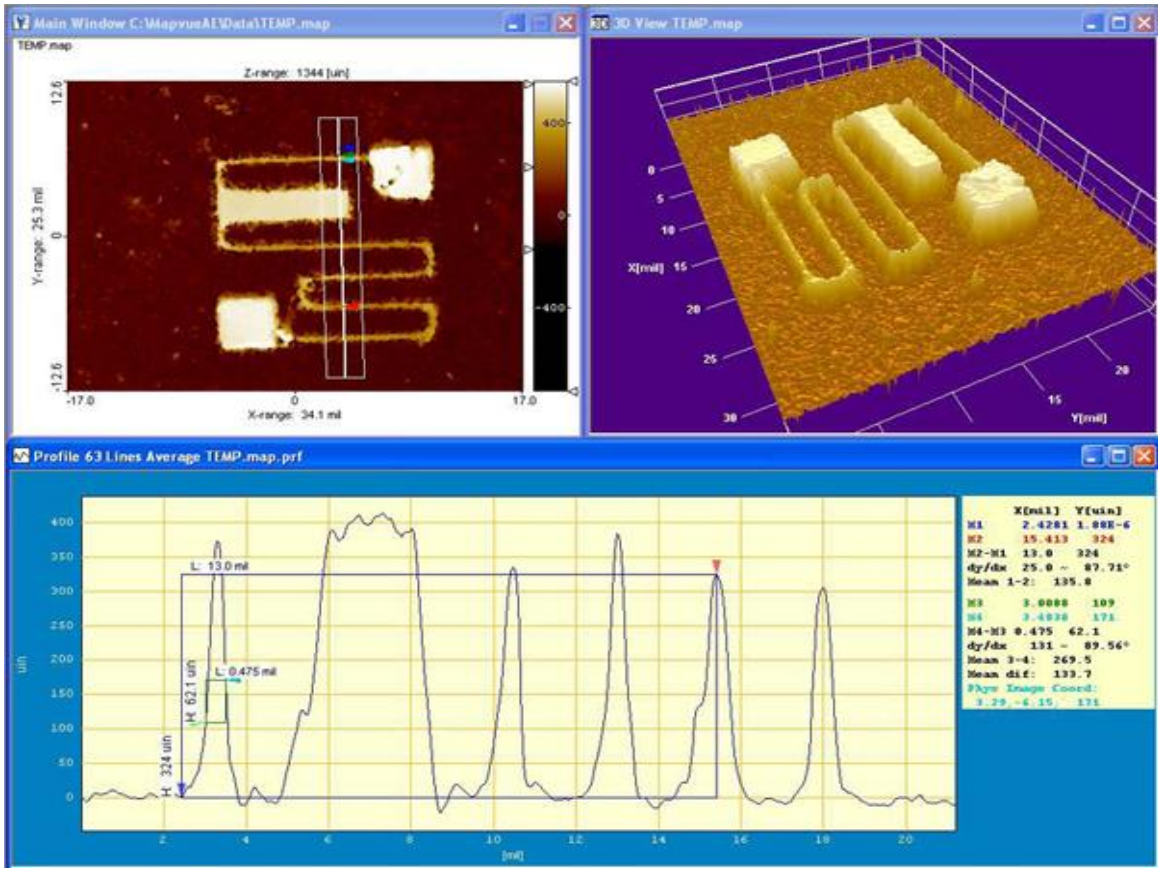


Figure 9

The 1 Gigaohm ultra low VCR 1000:1 Voltage Divider

A leaded divider was made using photo patterning. The intent of the exercise was to produce a 1 Giga Ohm device with extremely low VCR.

It was possible to achieve this goal with a 4 mil line with 2 mil white space gap between lines. The 48.35 inches of serpentine result in an aspect ratio of 12000, this allowed us to use an ink with a sheet resistance of 100K Ohms / square.

We were interested to know the manufacturability of a large area device with narrow white spaces. The device was manufactured on 96% alumina, to exacerbate any difficulties with line broadening while firing the thick film conductor. The conductor is applied after patterning the resistor, in our current process.

The design clearly demonstrates the benefits of a large aspect ratio, but does not take full advantage of the potential of photo patterning. An improved design should include trim sections commonly found in thin film designs, such as ladders and shunts Trimming should only be done on the high side element of the divider. The low side element should have the same width as the high side, and differ only in length. These improvements will improve tracking of VCR and TCR.

The following describes some of the characteristics of the device.

Each plate contains 14 devices. As patterned, the resistance range is typically 5%.

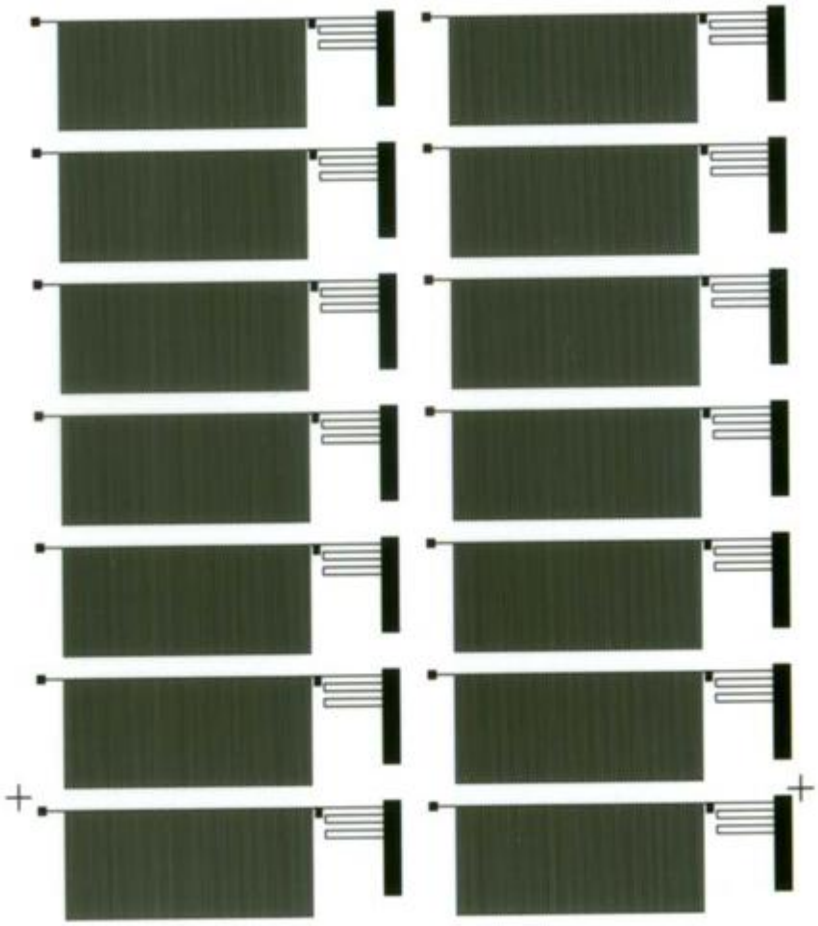


Figure 10

Figure 11 shows one of the devices. The shortcomings of the camera and printing do not faithfully capture the uniformity of the device.

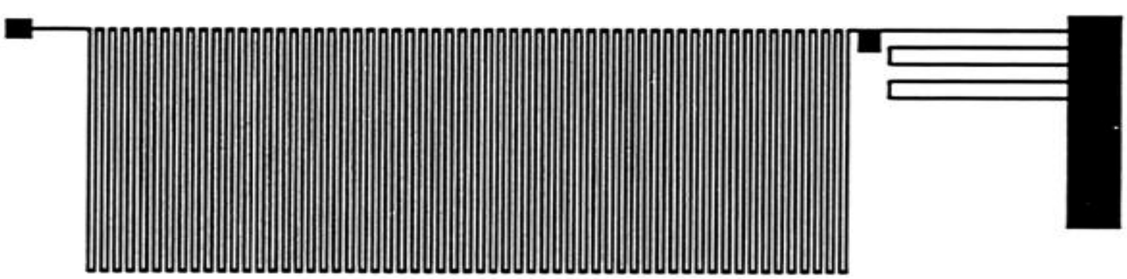


Figure 11

The following contour plot shows the topography of the lines. It is representative of the entire surface of the device. The uniformity of thickness and width at the ends of the loops is noteworthy.

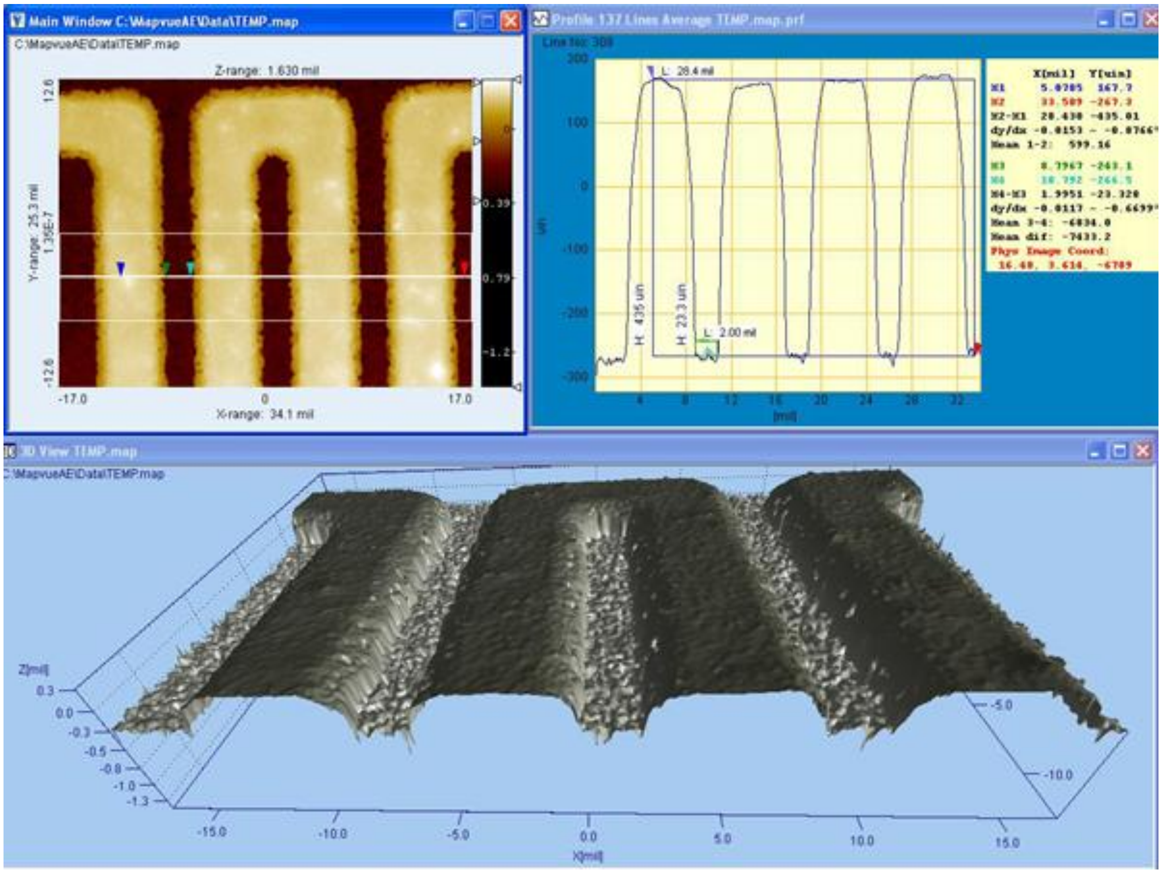
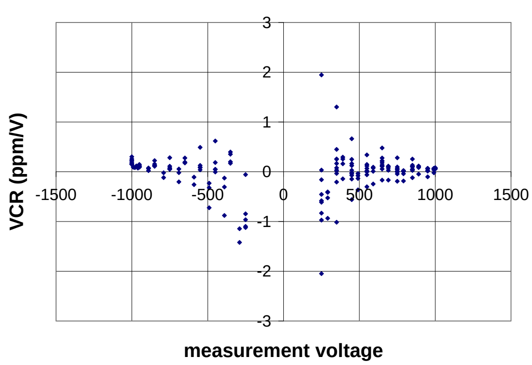
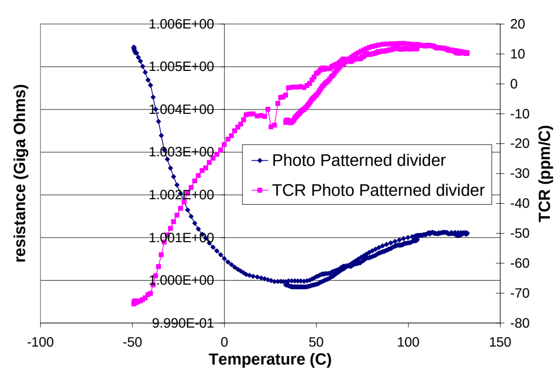


Figure 12

Performance

Devices were measured, using a Keithley 6517A Electrometer. Although the measurement is noisy at low voltages, the VCR is likely less than 1 ppm/V from -1000 to +1000V. The TCR, referenced to 25ºC, is less than 15 ppm/ ºC from room temperature to 130ºC.





A batch of plates was measured at 100 and 1000 Volts. The VCR was 0.03 ppm/V with a sample standard deviation of 0.03. The TCR of the devices was measured at 25ºC and 75ºC. The TCR was 5 ppm/ ºC, with a sample standard deviation of 5.

Conclusions

Very large aspect ratio serpentine resistors improve the electrical performance of high ohmic value thick film resistors by allowing the use of the most optimum materials. Photo patterning is a process which enables designers to realize the improvements in an eminently manufacturable way.

Benefits from photo patterned lines

- Uniform thickness and line width
- Reduced VCR
- Lower TCR
- Better tracking of TCR and VCR, in networks
- Lower Noise
- Better power handling
- Reduced variability increases yields
- Process feedback enables etching to value, accommodating for batch variability in screening.
- In process control enables 5% tolerance without trimming