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New Developments in Polymer Thick Film Resistor Technology

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Abstract
Motorola has been using embedded polymer thick film resistors on immersion silver-plated copper terminations in products for four years, and in the past year other firms have begun using this technology in their products. It is available to any electronic equipment maker from multiple board suppliers. Highly reliable resistors with values ranging from ohms to mega-ohms can be embedded in conventional HDI/FR-4 multilayer boards, providing cost savings and product size reduction. In this paper we present recent improvements in resistor materials and design. Resistor value predictability is improved with a simple innovation in termination design and the segmenting of low aspect ratio resistors. Resistor value distributions are improved with more thixotropic inks. Combined, these improvements allow 10-20% untrimmed tolerances (depending on ink resistance and production volume) for 0.25-mm-wide resistors. Tighter tolerances are possible with laser trimming.

Introduction
Among embedded passives technologies, resistors offer the greatest part count reduction and cost savings for most products. Whereas currently available embedded capacitor and inductor technologies are limited to the lower value ranges (< 300 pF and < 10 nH), embedded polymer thick film (PTF) resistors can cover the full range of resistor values, from ohms to mega-ohms. Automated measurement and laser trimming are also more practical with resistors, allowing <5% tolerances. As reported at the 2002 and 2003 conferences, we have been using embedded screen-printed PTF resistors in Motorola products since early 2000. In the past year other firms have also started using this technology to reduce product size and cost and achieve superior electrical performance.

We continue to seek improvements to PTF resistor technology that will enhance its utility in advanced electronics products. In this paper we will present some simple design innovations that allow resistor values to be pinpointed on the first pass, reducing cycle time, scrap, and cost. This requires that resistance exhibit linearity with respect to resistor length and width, within 5% of ideal behavior. Linearity is especially important for quick turn prototyping, for complex boards that have many different resistor values in the circuit, and for lower volume prints, for which prototyping scrap is not a negligible cost factor.

We will also present results of improved, more thixotropic low range (<100 ohms/square) inks that yield tighter as-printed tolerances, especially at smaller resistor dimensions.

Resistor Value Predictability
Figure 1 shows an example of a simple diagnostic tool used in printing resistors in a new board design. The chart's upper portion shows individual resistor values with respect to the target value. The lower portion shows the mean value with respect to the target value. A large number of resistor values is being printed. The resistor value distributions are good – typically ±10% of the mean value. Many research studies of embedded resistors equate such distributions with achievable tolerances. However, in the production of real circuits, tolerances are referenced to the target value, not the mean value. Figure 1 shows that the mean values can vary significantly from the target values: in this example, most of the resistors are more than 20% below the target values.

Resistor value is in theory determined by the simple equation:

$$R = \rho_s L/W \qquad (1)$$

where ρ_s is sheet resistance and L and W are resistor length and width. PTF resistor values can be adjusted by two means. The first is by adjusting the sheet resistance. Subtle adjustments to sheet resistance are possible by changing the print thickness by varying print speed and other machine parameters. Larger adjustments are made by blending the ink. In the Figure 1 example, all of the resistor mean values are below target. Blending the ink with a higher value ink in accordance with a standard blending formula will raise the mean values of all resistors. However, because the mean values vary from –5 to –35% below the target values, tolerances will still be poor when these mean values are shifted higher by the ink blend. The second means of adjusting resistor values must be employed: adjusting the resistor dimensions. This allows resistor values to be adjusted individually, with the goal of achieving a flat line in the lower portion of the Figure 1.

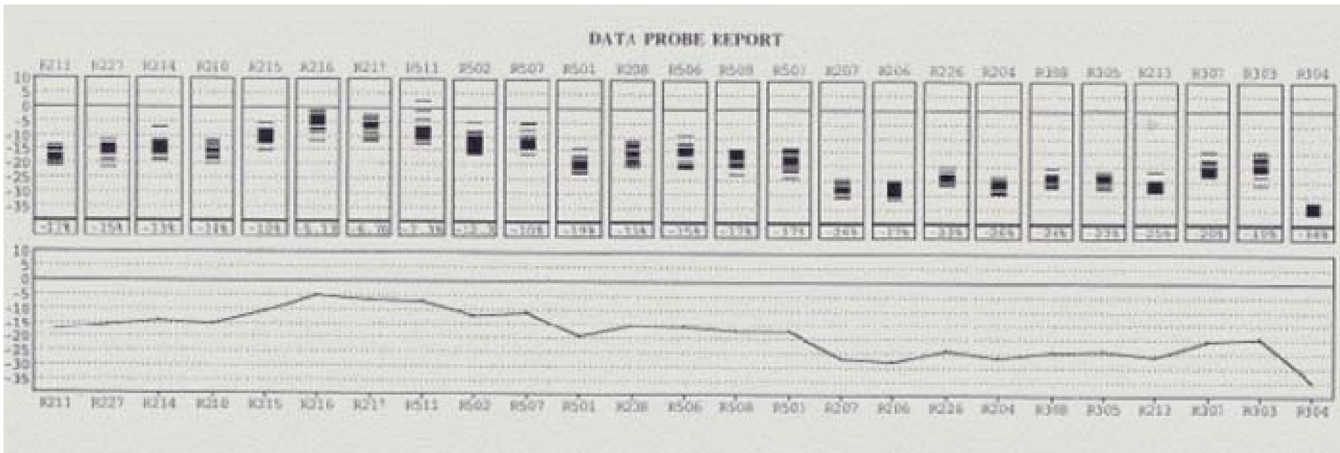


Figure 1 – Resistor Value Distributions from a First Article Print of a Complex Product

Resistor width is most easily adjusted, because resistor length is set by the spacing between the copper terminations. The resistor widths are individually adjusted in the CAD layout, new artwork is generated, and a new screen is fabricated. This process can take several hours. Figure 2 shows why this process is necessary, and Figure 3 shows why it is not straightforward and may require several iterations to achieve optimal results.

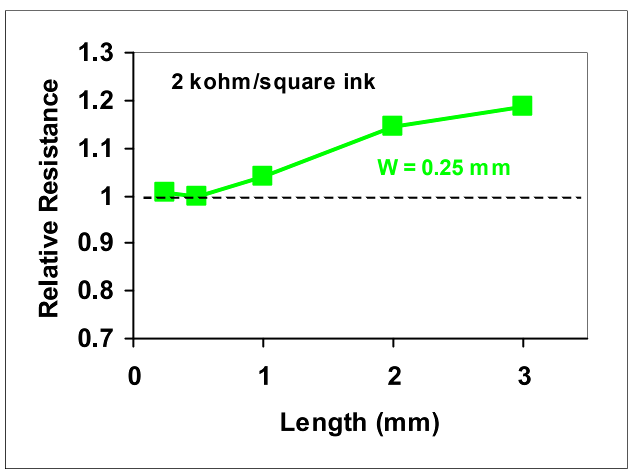


Figure 2 – Relative Resistance (Actual vs. Theoretical) as a Function of Resistor Length, for 0.25-mm-Wide Resistors Printed Parallel to the Squeegee with 2 kohm/Square Ink (Similar Behavior is Observed with other Value Inks)

Figure 2 shows data from a test board printed with 2 kohm/square ink (similar results are obtained with other value inks). Relative resistance is plotted vs. resistor length. Equation 1 predicts that the data should fall on a flat line at 1. The deviation from this ideal shows that resistance is not proportional to length. This is due to mechanical effects as the print squeegee moves across the resistor terminations. (We typically print resistors sideways – that is, with the squeegee parallel to resistor length – because we have observed some resistor failures in thermal shock for very short resistors printed orthogonal to the squeegee. We believe this may be due to "pinching" of the ink against the far termination as the squeegee completes the print, resulting in vulnerability to cracking at this site as the resistor is stressed by thermal expansion mismatch between the copper and the FR-4.) The squeegee is held off the board surface at the resistor's distal ends by the copper terminations (typically about 12 μm thick). For longer resistors, however, there is some deflection of the squeegee towards the board surface in the resistor mid-span, resulting in a thinner resistor cross section there. This violates the assumption of uniform sheet resistance that is implicit in Equation 1, and causes longer resistors to have higher resistance than predicted. Because the resulting behavior is non-linear, as shown in Figure 2, and moreover may vary from lot to lot and design to design, due for example to copper thickness variation, designing embedded resistor geometries with good value predictability is very difficult, and empirical adjustments in production are needed.

Figure 3 shows why such empirical adjustments are difficult. As noted above, the resistor length is set by the copper terminations, so the printer adjusts resistor values by changing the width. The printer assumes a linear dependence of resistance on width per Equation 1, modifies the widths of individual resistors in the CAD layout, generates new artwork, makes a new screen, and prints a second prototype to determine if the mean values are now lining up on the target values. Figure 3 shows why he is often disappointed: the relationship between resistance and width is not linear either (for reasons we will discuss shortly). Moreover, the printer is typically making adjustments in the steep part of this curve: the starting width of the resistor is typically 0.25 mm in our designs. Put another way, the designer and printer, in using Equation 1 to set length and adjust width, respectively, are working on a two-dimensional curved surface but assuming they are on a flat plane.

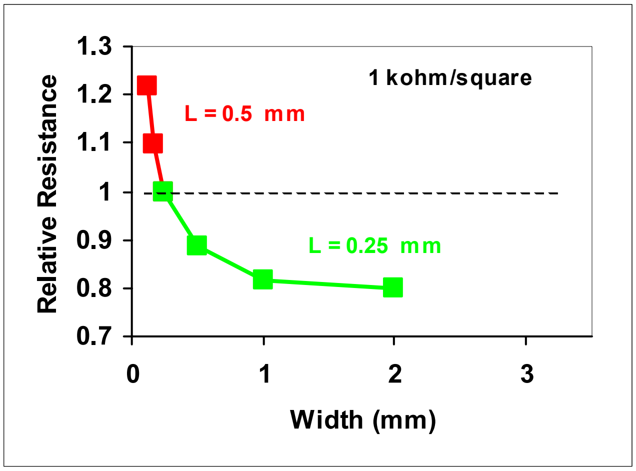
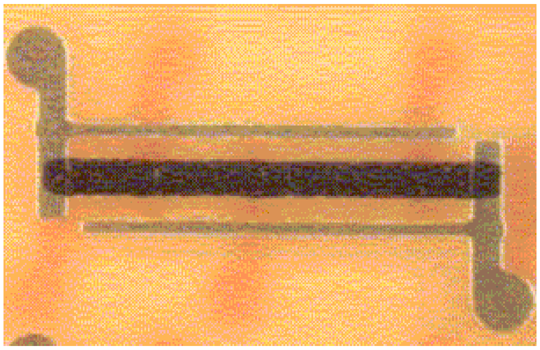


Figure 3 – Relative Resistance (Actual vs. Theoretical) as a Function of Resistor Width, for 0.25-mm- and 0.5-mm-Long Resistors Printed Parallel to the Squeegee with 1 kohm/Square Ink (Similar Behavior is Observed with other Value Inks)

Thus, while PTF resistor technology offers the advantage of flexible adjustments through machine parameter changes, ink blending, and artwork modifications, such adjustments take time and increase scrap and cost. This is an increasingly important problem as we move to more complex designs with larger numbers of resistors printed with a single ink. Quick turn prototyping is prevented by the need for several iterations of artwork adjustment to "tune" all resistor values.

Figure 4 shows the simple solution to this problem. Copper termination "fingers" running parallel to the resistor edge provide topographical uniformity in the resistor print area, preventing squeegee deflection (this may not be intuitive for a squeegee parallel to the resistor, but bear in mind that the resistor print area is on the order of 0.5 mm wide, and therefore small relative to the squeegee edge acting through the screen). The result is excellent linearity of resistance vs. length. Boards can now be designed with multiple resistor values by adopting a standard width (0.25 mm is typical in our designs) and varying length to change resistance. The need for artwork modifications is eliminated for resistors from 0.25 to 2.5 mm long (1 to 10 squares).

We considered the possibility that the copper fingers were having a thermal rather than – or in addition to – a topographical effect. That is, one could hypothesize that the observed nonlinearity was due partially or even primarily to thermal nonuniformity during resistor cure. According to this theory, during cure the resistor is cooled by solvent evaporation, but the ink adjacent the copper terminations is maintained closer to ambient temperature by heat conduction through the copper. The result is a nonuniform cure along the length of the resistor, with the mid-span less cured and therefore more resistive. We tested this theory by forming termination fingers with nonconductive, screen printed solder mask. These polymer fingers could be expected to mimic the topographical effect of copper fingers, but not any thermal effect. We observed that the polymer fingers had substantially the same impact on resistor values as the copper fingers, supporting topography as the main effect.



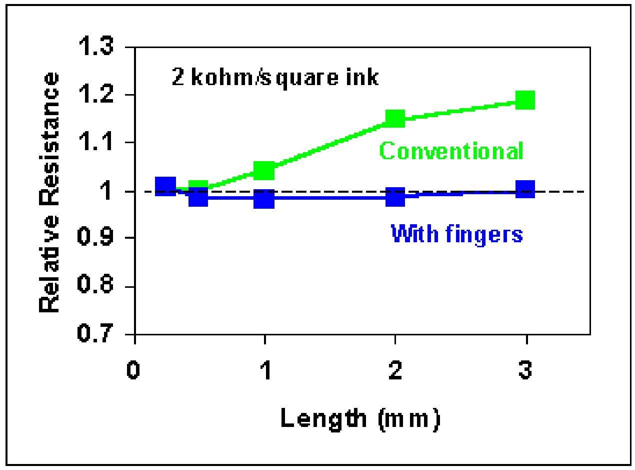


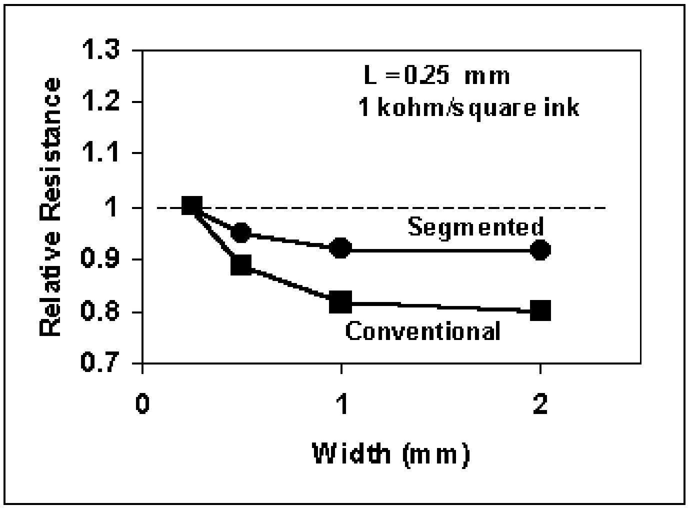
Figure 4 – Effect of Termination "Fingers" on Relative Resistance: Nonlinearity is Eliminated

Achieving a linear relationship between resistance and length is not adequate, however. Varying length from 0.25 to 2.5 mm while holding width constant at 0.25 mm provides a one order of magnitude range in resistance with a given ink. Reducing length substantially below 0.2 mm is undesirable because at these dimensions laser trimming becomes problematic. Increasing length above 3 mm is undesirable because the resistor is then quite large, and, even though space is often plentiful on board inner layers, parasitic effects and interference with routing become a concern. However, it is typically desirable to cover 1.5-2 orders of magnitude of range with a single ink. For example, a product employing resistors from 5 to 500 ohms could then be printed with a single ink (40 ohms/square, with aspect ratios ranging from 1/8 to 12.5 squares), or a product employing resistors from 10 ohms to 1 megaohm could be printed with three inks (40, 2000, and 100,000 ohms/square), each printed and cured separately. Additional range can be had by extending each ink at the low end: viz., by making resistors wider for aspect ratios below one square. However, that puts us back on the nonlinear R vs. W curve of Figure 3.

Why should resistance not be linear with width? Consider that the resistor cross section is not rectangular, but rather of an irregular trapezoidal shape due to some flow or "slump" of the ink when it is printed. Consider furthermore that the print surface – the surface of the FR-4 after the toothed copper has been etched away – is very rough, with peaks and valleys of several microns. The feathered edges of the resistor cross section are thus on the same order as the surface roughness: the ink will fill the valleys, but a continuous conductive path is barely established over the peaks. In short, this thin edge region of the resistor will not contribute significantly to conduction. This is one cause of nonlinearity: these edge regions of the resistor comprise a large fraction of a narrow resistor, but a small fraction of a wide resistor. For this reason, a 1-mm-wide resistor will have a lower resistance than would be extrapolated from a 0.25-mm resistor, consistent with the data in Figure 3.

This problem is circumvented by segmenting wide resistors such that they are not just theoretically, but *actually* the same as multiple one-square resistors printed side-by-side. The improvement in linearity is evident in the data plotted in Figure 5. Perfect linearity still eludes us. This may be due to thermal effects: since the black ink is an effective infrared absorber, multiple resistors printed in such close proximity may lead to a higher local temperature, and thus a greater degree of cure and decreased resistance. Nonetheless, the simple solution of segmenting brings the nonlinearity to within 8%. This small variation can be anticipated in design to achieve good predictability.

In summary, good resistor value predictability, with concomitant savings in prototyping cycles, scrap, and cost, is provided by using termination fingers for aspect ratios above one square, and the segmented design for aspect ratios below one square. Both improvements increase resistor size, but only by 10-20%. For example, the termination fingers add 0.075 mm to each edge of a 0.6-mm-wide resistor (0.25 mm resistor width plus 0.175 mm of misalignment allowance), and segmenting a ½-square resistor adds 0.075 mm to its 0.8 mm width.



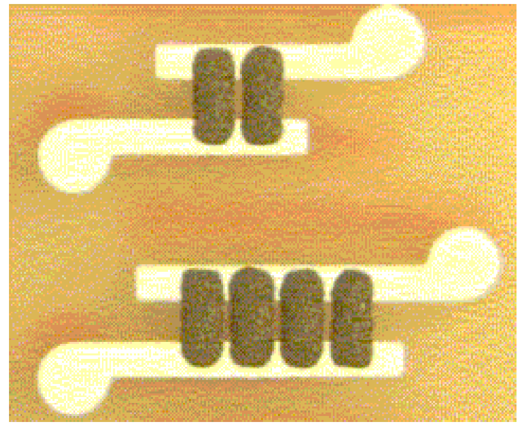


Figure 5 – Segmented Resistors for Improved Linearity of resistance with Width

Further Size Reduction and the Benefits of Highly Thixotropic Ink

The simple design innovations discussed above allow good resistor tolerances to be achieved without artwork iterations. Our best results have been with kilo-ohm range inks that are highly thixotropic. A highly thixotropic ink flows easily upon the application of the squeegee shearing force, but ceases flowing once it is deposited on the board, resulting in well-defined resistors, even at 0.25-mm widths. 3-4% coefficients of variation (standard deviation divided by the mean) and 10% tolerances can be routinely obtained for 0.25-mm-wide resistors printed across 16 x 20 inch FR-4 panels. This is remarkable when one considers that a 325# screen provides only about three apertures across the width of such a narrow resistor.

Higher value inks are more challenging, containing as they do a smaller portion of carbon particles and a larger portion of phenolic resin, and depending therefore upon fewer carbon-to-carbon contact points for conduction, but we have worked over the past two years to improve the consistency of 100-kohm/square ink, in terms of resistivity, thixotropy, and shelf life. Untrimmed (as printed) 20% tolerances are routinely achievable for 1-megaohm resistors.

Newly formulated low range inks (30-100 ohms/square) are now also available. These inks mimic the excellent thixotropic properties of the established kohm-range inks. A comparison of the old and new inks illustrates how important these properties are to achieving good resistor tolerances. In Figure 6, coefficient of variation (CV) is plotted vs. resistor length for three different widths: 0.25, 0.175,and 0.125 mm (10, 7, and 5 mils). On these test boards we obtained somewhat high CV's (4-5% vs. 3-4%), but the differences between the inks are still apparent, particularly as width is reduced. With the 1 kohm/square ink, we were able to obtain 5% CV even at W = 0.125 mm (5 mils). At this size the resistor width spans fewer than two apertures in the screen, and the resistor occupies less space than even an 0201 surface mount component.

The data for W = 0.25 mm include resistors with lengths down to 0.1 mm. At these lengths the CV data for 40 ohm/square ink are strongly influenced by measurement artifacts: the probe contact resistance can be a significant fraction of the total resistance for aspect ratios below ¼-square (10 ohms).

We recently used the improved low range ink and termination fingers to print a low volume product with more than 60 embedded resistors. We achieved 2-4% CV's and 10% tolerances without trimming.

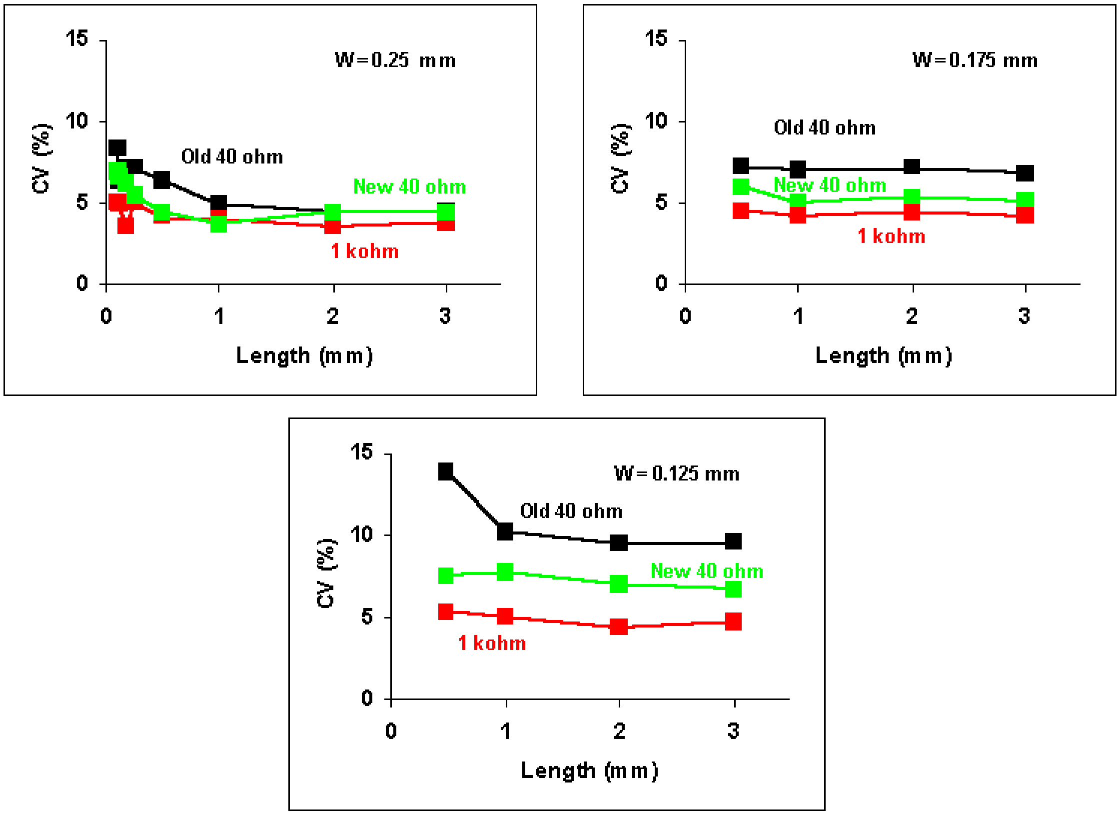


Figure 6 – Coefficient of Variation (CV), or Standard Deviation Divided by the Mean Value, vs. Resistor Length for three Different Widths (10, 7, and 5 mils) and Three Different Inks - The "New 40 ohm" Ink was Formulated to have a Higher Thixotropic Index, and Behave more like the 1 kohm/Square Ink

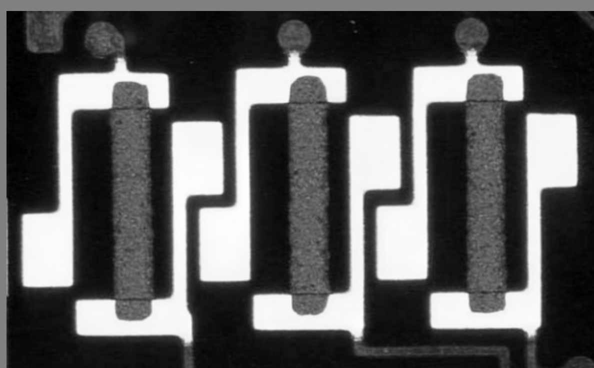
Conclusion

Motorola has had products with embedded PTF resistors in the field for four years. The technology is cost effective, highly reliable, and available to any electronic equipment maker from multiple board suppliers. Using the inks and design methods discussed in this paper, 10-20% untrimmed tolerances, 3% laser trimmed tolerances, and ±5% stability are readily achievable for resistor values ranging from ohms to mega-ohms. Boards with up to 150 embedded resistors and panels with up to 20,000 resistors are in production now. While some fraction of resistors will always be kept as surface mount devices – for bench tuning or exceptional tolerance, stability, or power handling requirements – most resistors in a typical circuit for a handheld device can be removed from the surface with this technology, allowing cost savings and product size reduction.

Acknowledgments

We are indebted to Rummy Makmur of IBIDEN Circuits of America for fabricating the boards used in this study, and to Barrie Jones for many helpful discussions on PTF technology.

New Developments in Polymer Thick Film Resistor Technology



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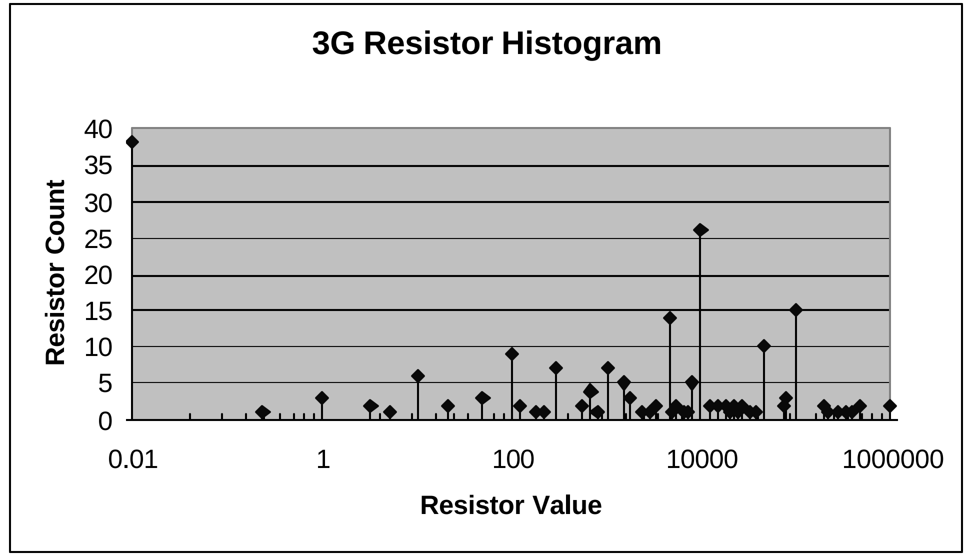
Outline

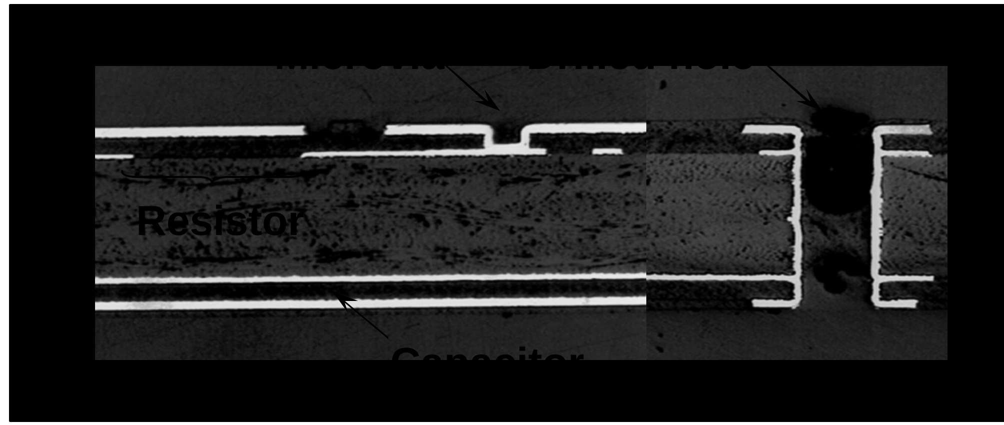
- Introduction
- New resistor designs for superior linearity
- Improved low value inks

Embedded Resistor Challenges



- Wide distribution of values
  - ➢ Embedding technology must capture wide range of Rs
- Very low Direct Material cost (approx. $ 0.15 for 2.5G)
  - ➢ Embedding technology must be very cost effective
- Assembly cost is 4X Direct Materials cost
  - ➢ Assembly cost saving and space saving is a key driver

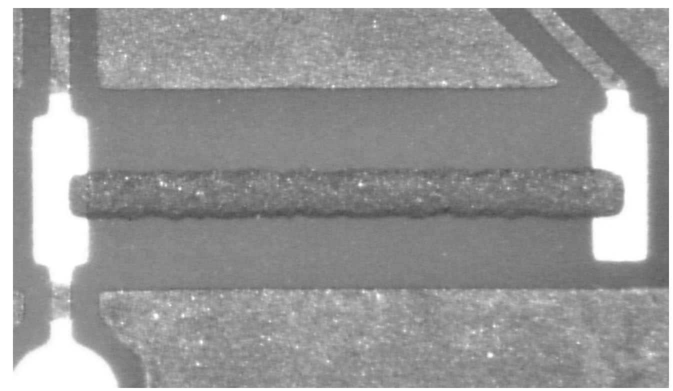
Embedded PTF Resistors



- Product size reduction
- Part count reduction
- Cost savings
- Used in Motorola products since January 2000
- Fully compatible with conventional circuit board manufacturing
- 30-50% of all passives
- Unlike C’s and L’s, any value can be embedded – 10 Ω - 1 MΩ

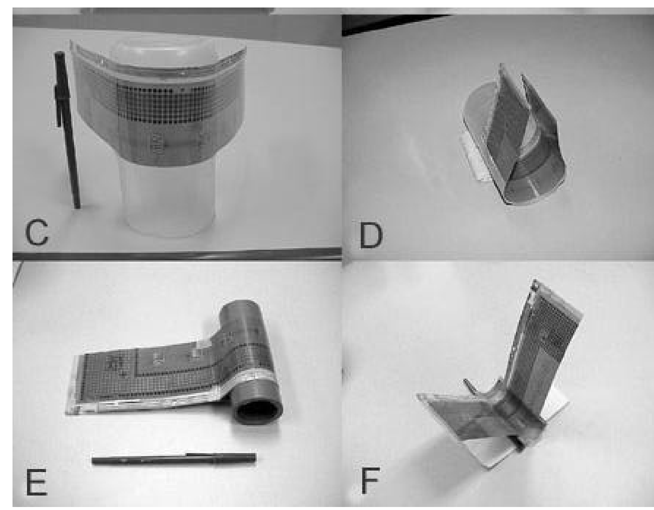
Resistor Stability

- ±5% under all conditions as a general rule of thumb
  - Higher resistance inks show greatest changes
  - <10% reversible change after 1000 hours 85/85, not representative of field performance
- Must be terminated on immersion silver on ½ oz copper or thinner
- Must be printed parallel to squeegee
  - Some failures of orthogonal short resistors in 1000 cycles thermal shock



Resistor Reliability Testing

- 1000 hours 85°C/85% RH
- 1000 cycles thermal shock (-55°C to +125°C)
- 1000 hours at 125°C
- 1000 bend cycles on a 3.5” mandrel (.005” FR-4)
- Board-level, module-level, and phone-level ALT
- Products in the field for four years
- Power handling not an issue for handheld products, but must be considered for higher power applications
- Substantially more robust under ESD vs. thin film resistors



New Resistor Designs for Superior Linearity

3/25/03

Definitions

- CV = standard deviation divided by mean value

- Relative resistance $= \dfrac{\text{resistance}}{\text{(\# squares x resistance of 1 square)}}$
  - Ideal value is 1

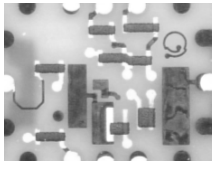
Tolerances

- Direct comparison of published “tolerance” data for different resistor technologies not typically valid
- Tolerance is a production spec that depends on:
  - Panel dimensions (larger is more challenging)
  - Resistor dimensions (smaller is more challenging)
  - Number and range of resistor values (wide range more challenging)
  - Number of resistors per board, panel, and lot
  - Linearity of resistance with length (for predictability)
  - Ease of adjustment (e.g., ink blending, artwork modification)
  - Board-to-board, hour-to-hour, day-to-day, lot-to-lot variation
  - Volume (high volume more challenging)
  - Desired yield
- Our experience is that 2-6% CV is sufficient for 20% tolerances and 1.3 CpK in volume production

Circuit Complexity

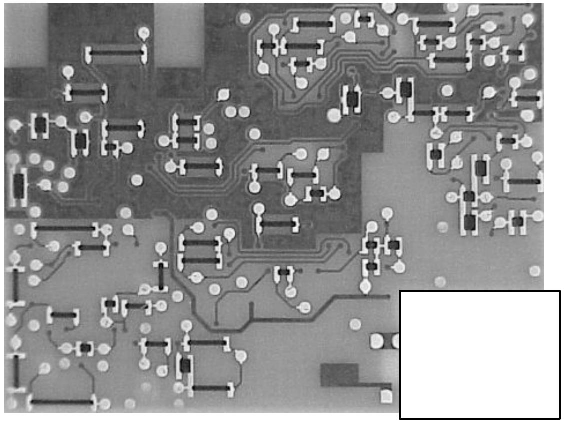
2000

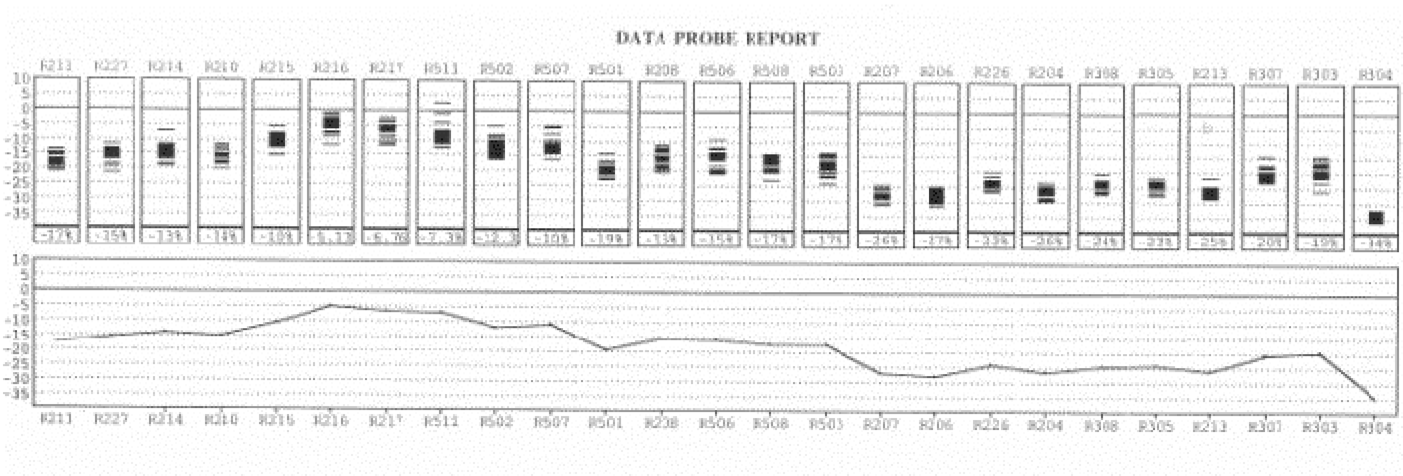
- < 10 resistors/module
- 2 inks
- 2 order of magnitude resistance range



2003

- > 50 resistors/board
- 3 inks
- 5 order of magnitude resistance range
- Resistor value predictability is critical





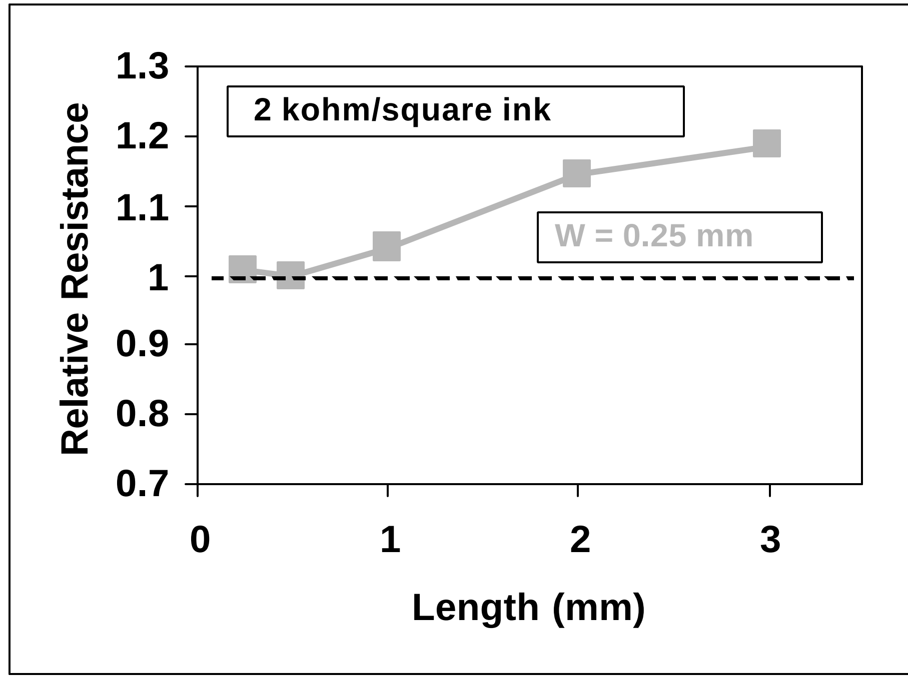
- Good resistor tolerances can only be achieved when value distributions (CV's) are narrow *<u>and</u>* mean values are very close to target values
- In this example, 25 resistors are being printed with one ink
- Distributions are good: all values are ± 20% of means
- But the mean values are 5-30% below the target values

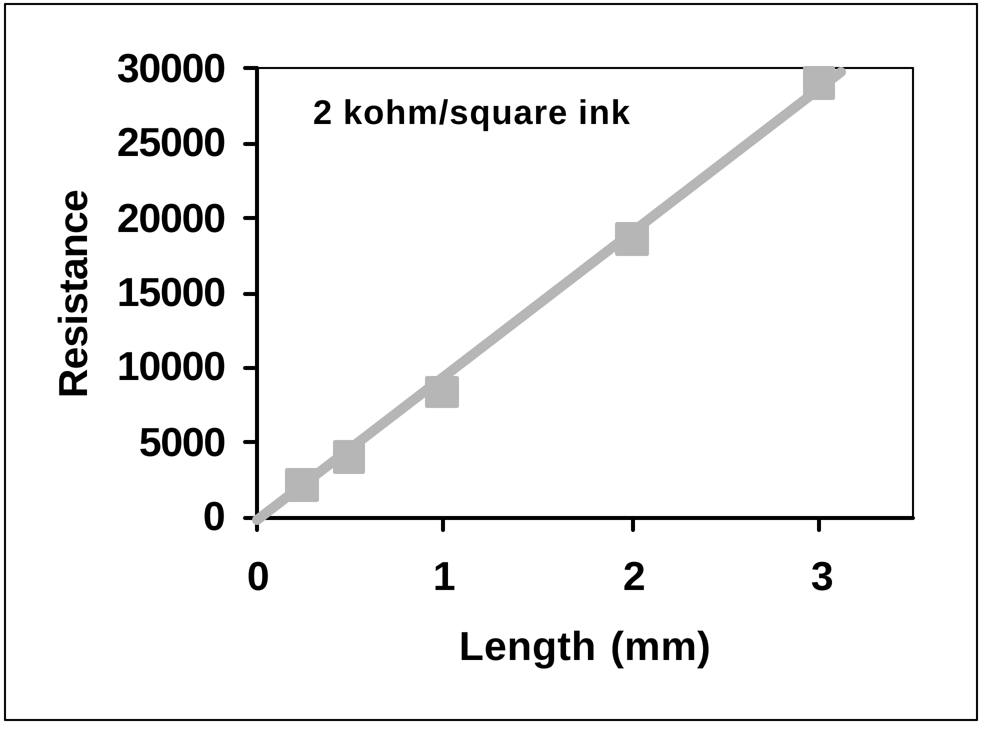
- In theory,

$$R = \rho_s L/W$$

- In practice,

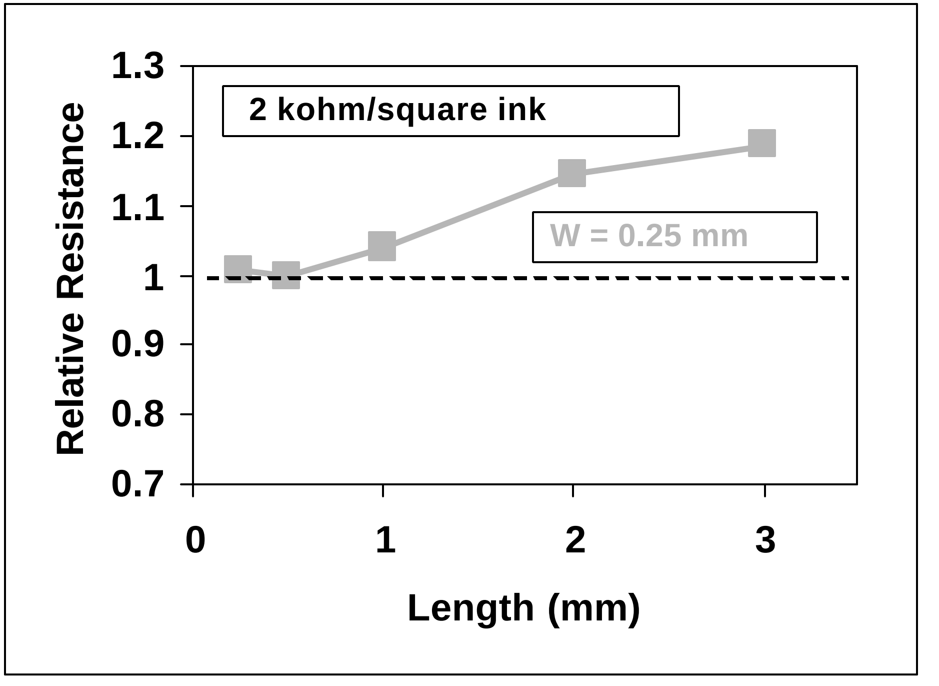
$$R \not\propto L$$





- Plotting resistance vs. length is inadequate for detecting 1-20% deviations from linearity

- Resistor is printed thinner in mid-span due to deflection of the squeegee between the terminations
- This leads to higher resistance per unit length vs. a short resistor
- Degree of nonlinearity varies with copper thickness and ink thixotropy, precluding accurate resistor value predictions
- Local topography (copper features) affects each resistor, leading to differing results for the same resistor in different board locations



Prototype Cycles

- In theory,

$$R = \rho_s L/W$$

- Two means of adjustment are available:
  - Blend the ink to increase ρ_s (all resistors increased)
  - Adjust resistor widths and make a new screen (selective adjustment of each resistor)

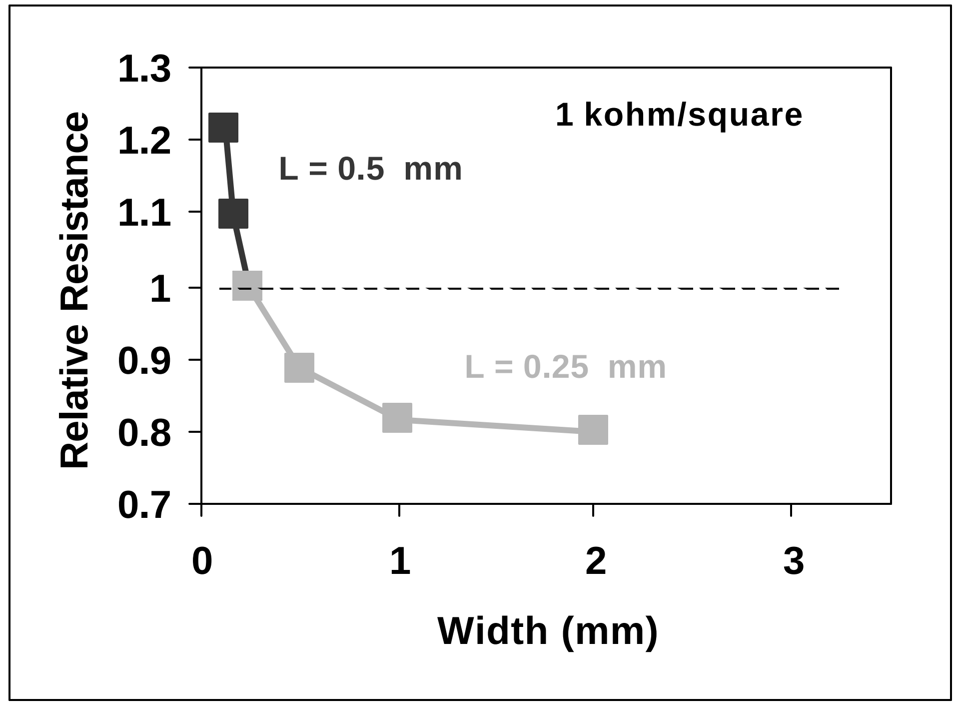
- In theory,

$$R = \rho_s L/W$$

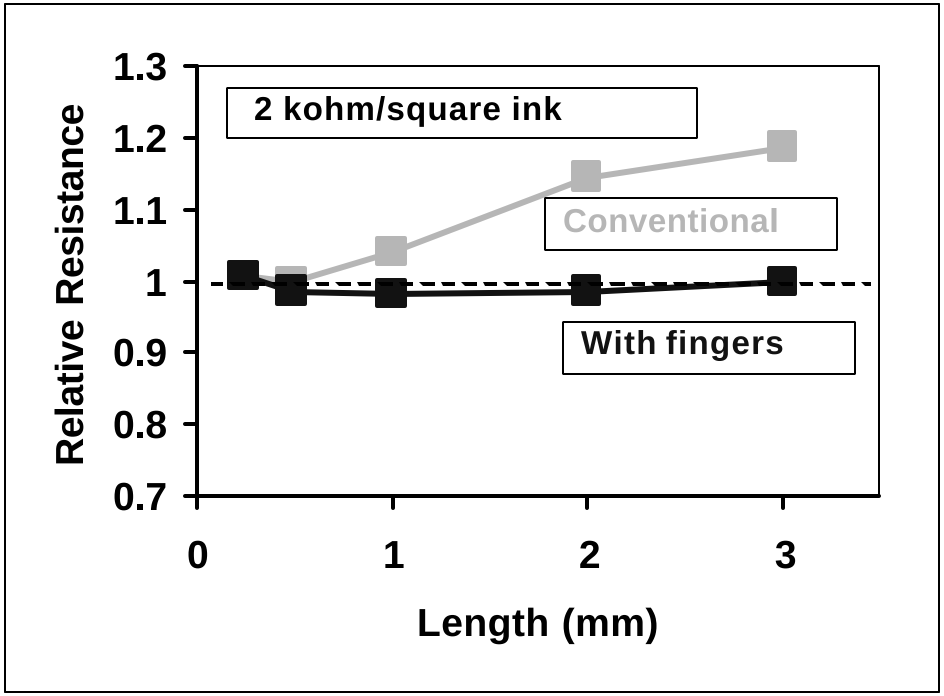
- In practice,

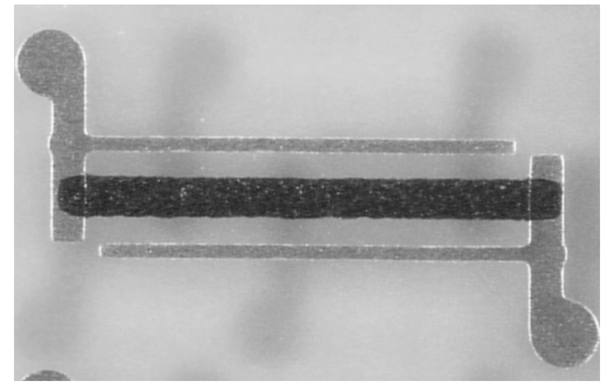
$$R \not\propto 1/W$$

➢ Adjusting resistor widths is problematic

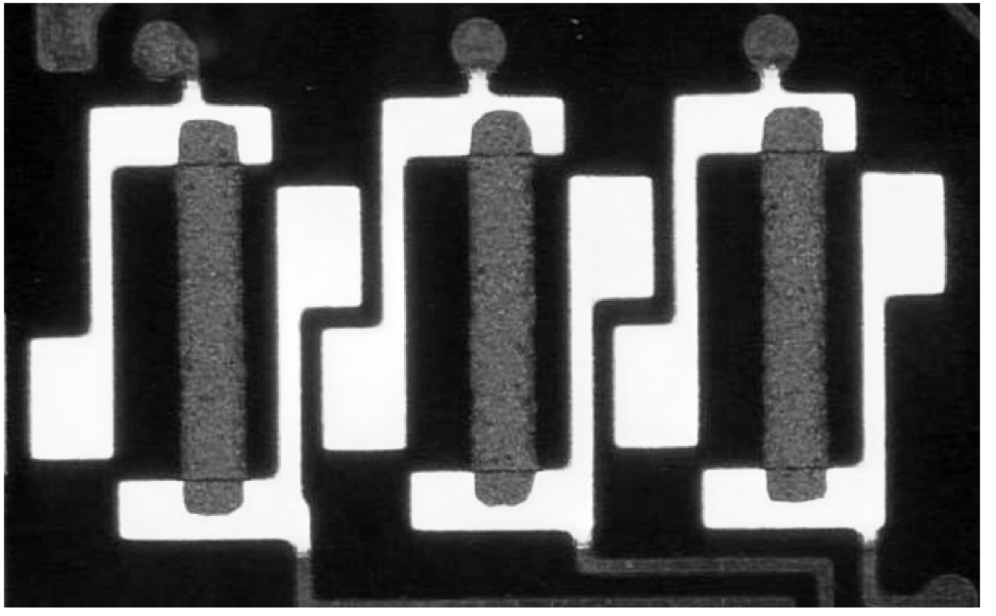


The Solution

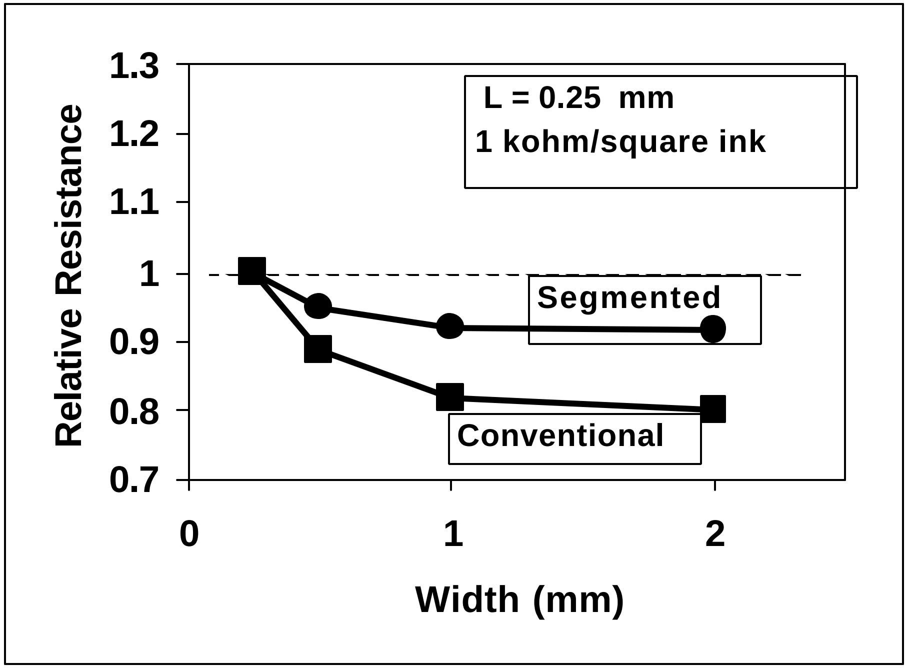


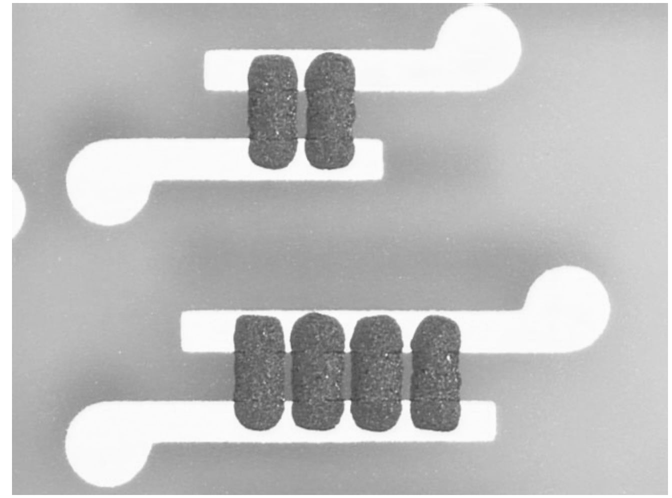


- Termination “fingers” prevent deflection of the squeegee and provide a linear R vs. L relationship



- All or a portion of the finger can be combined with the test pad

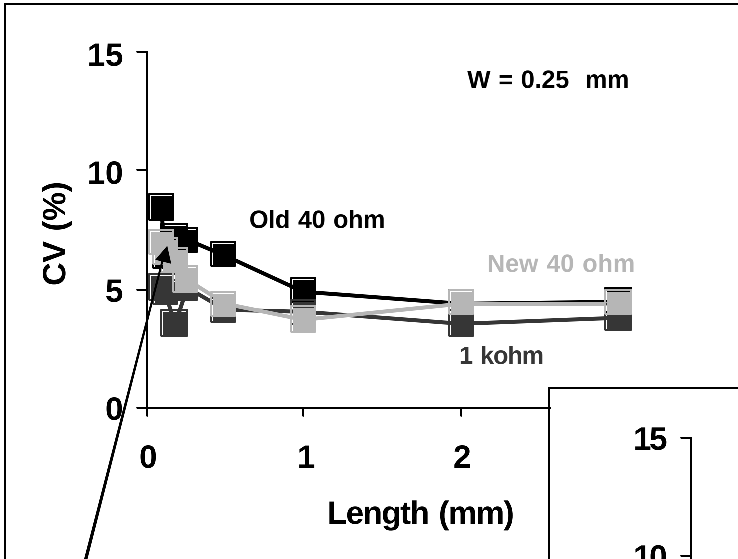


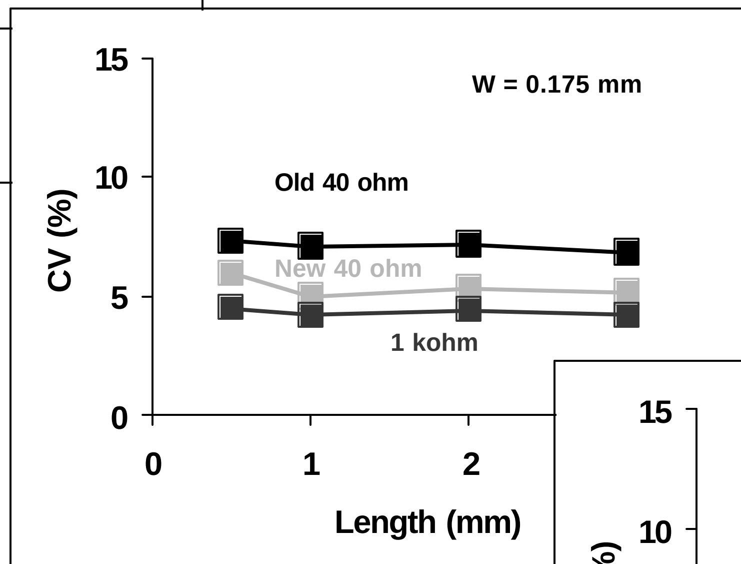


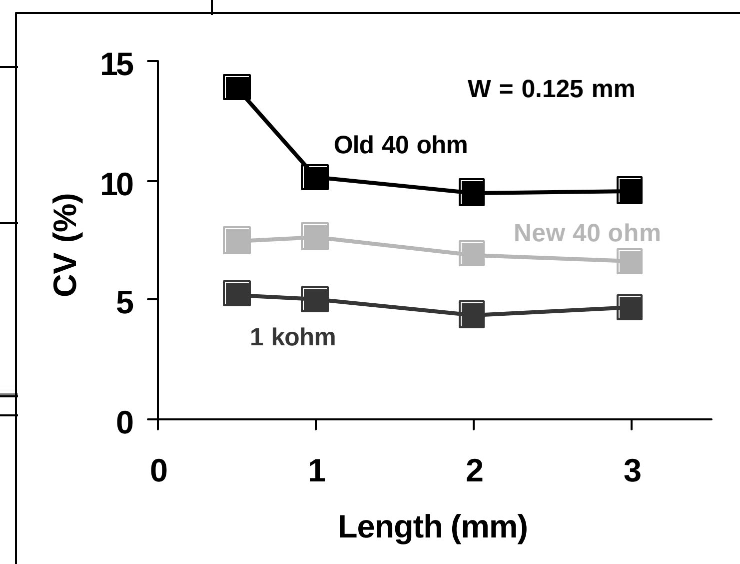
- The challenge of resistors < 1 square remains
- Increasing W when L is at a minimum (0.1 – 0.25 mm) allows the range of an ink to be extended to lower value resistors
- Segmenting the resistor into stripes, with 0.08 mm gaps, mitigates, but does not entirely eliminate the problem

Improved Inks

- Thixotropy of ink is increasingly important for small resistor geometries
- The new Asahi inks will allow improved yields and smaller resistors



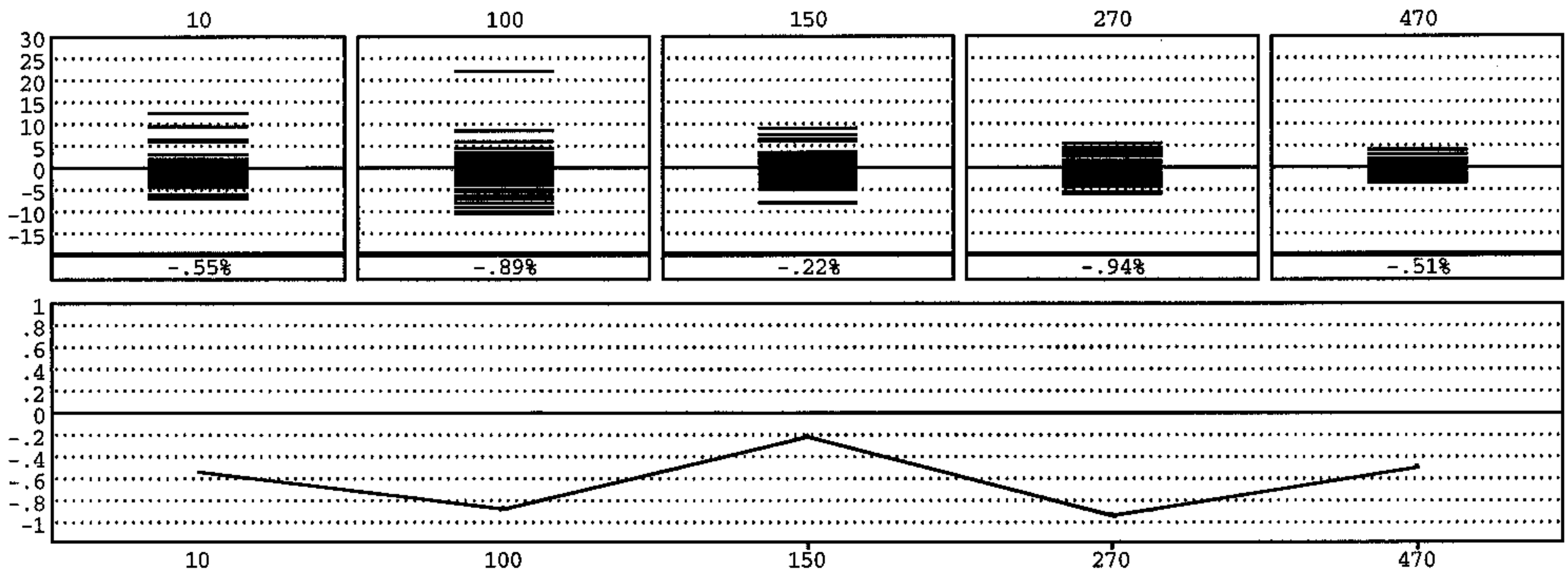




At very short resistor lengths, copper edge variation and (for low resistance inks) measurement probe contact resistance variation are contributing factors

MOTOROLA

DATA PROBE REPORT



- The combination of termination fingers and the new ink allows excellent resistor tolerances

Alternative Resistor Technologies

Alternative Resistor Technologies

- We have investigated many other resistor technologies, including side-by-side production comparisons with PTF
- None can match PTF’s reliability
- None offers superior tolerances
- None can match PTF’s very low cost
- None can match PTF’s range (ohms to mega-ohms)
- None allows multiple sheet resistances on one layer
- None offers simpler processing
- Most have not been demonstrated in high volume production and proven in the field

Summary

- Improved resistor value predictability with new designs
  - reduced cycle time and scrap
  - improved tolerances at the same CV's
- Highly thixotropic inks provide superior CV's