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Test Structures to Characterise a Novel Circuit Fabrication Technique that uses Offset Lithography

A. J. Walton, J. T. M. Stevenson, M. Fallon†, P. S. A. Evans‡, B. J. Ramsey‡, D. Harrison‡

Department of Electrical Engineering
University of Edinburgh,
Edinburgh, EH9 3JL, UK.

‡Department of Design
Brunel University
Egham, Surrey, TW20 0JZ, UK

†National Semiconductor
Larkfield Industrial Estate
Greenock,PA16 0EQ, UK

Abstract This paper reports on the use of microelectronic test structures to characterise a novel fabrication technique for thin-film electronic circuit boards. In this technology circuit tracks are formed on paper-like substrates by depositing films of a metal-loaded ink via a standard lithographic printing process. Sheet resistance and linewidth are electrically evaluated and these compared with optical and surface profiling measurements.

1. Introduction

Conductive Lithographic Films (CLFs) is an emerging fabrication technique that has the potential for application in a wide range of electronic circuits and systems. The process employs standard lithographic printing technology to fabricate conductive film patterns on a range of flexible paper-like substrates using purpose-developed conductive inks. The substrates can be printed rapidly, via a one-stage printing process, and are consequently cheap to produce. The films are robust, withstanding a range of standard environmental test regimes.

In order to apply an offset lithographic process for circuit fabrication, a comprehensive knowledge is needed of all aspects of the method. Critical elements include the ink characteristics, the printing plate, the fountain solution and the printing machine. In short, the comprehensive characterisation of the process and materials is essential.

The lithography relies on the action of two wetting functions on the surface of a smooth and un-embossed printing plate. The plate chemistry repels water where the printed image is dark, allowing an oil-based ink to adhere. A water film repels the ink in light regions of the image. Contact with an ink and a moistening roller allows the printing plate to attract both water and ink as required, and to form the image to be printed. The image is not printed directly onto the substrate material (e.g. paper), but is instead transferred to an intermediate or blanket cylinder that has a yielding surface. The blanket cylinder then presses the ink film onto the surface of the substrate, which is now supported on a separate impression cylinder. The printed substrates rely on evaporation and/or oxidation of the ink film to fix the image.

Initial investigations of the technology had indicated that sheet resistance and linewidth were functions of the type of "paper substrate" used and test structures have been employed to help quantify both parameters and their variability.

2. Test Structures and Measurement

A number of test structures have been designed and are illustrated in figure 1.

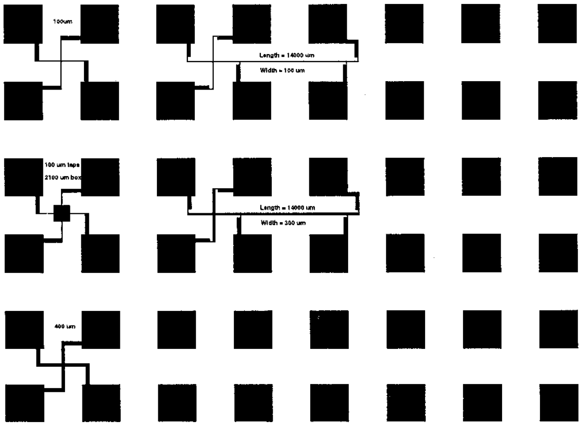

Figure 1. Test structures printed using CLF technology.

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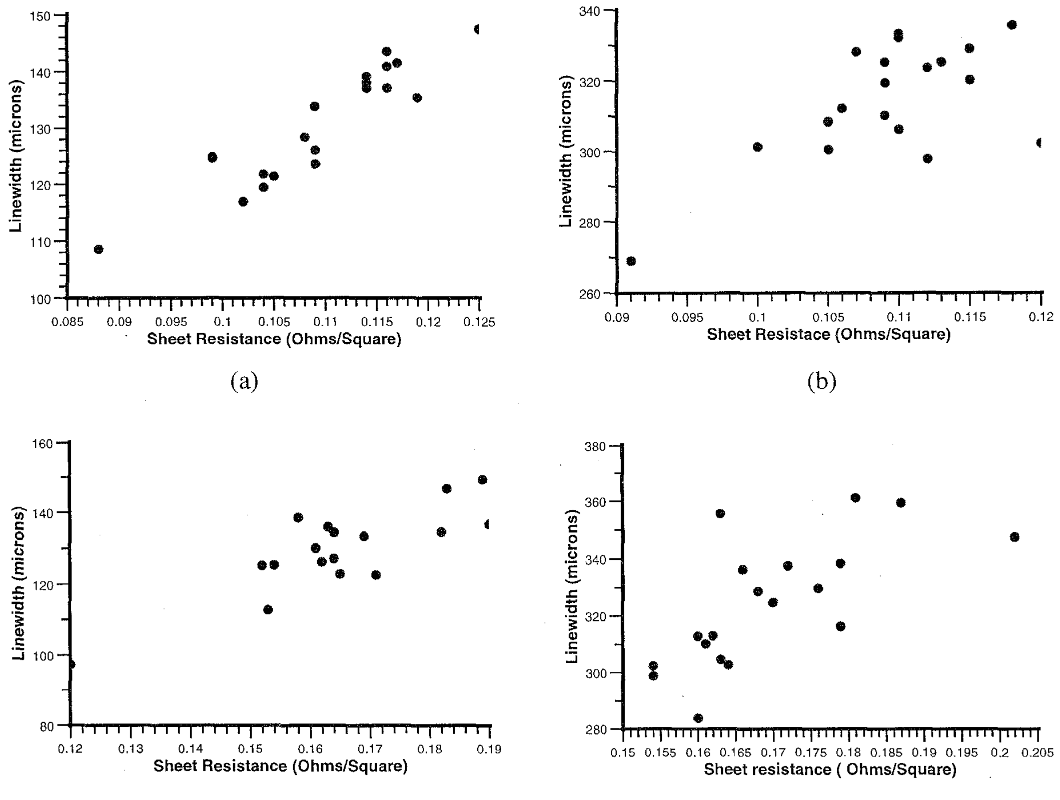
	Paper type	Greek Cross (100 μm) Ω/□	Greek Cross (300 μm) Ω/□	Box Cross Ω/□	Linewidth (100 μm) μm	Linewidth (300 μm) μm
Mean	Gloss	0.156	0.225	0.203	129.4	324.4
Values	Poly	0.104	0.130	0.125	130.5	314.5
Standard	Gloss	0.0146	0.0161	0.0185	12.2	22.1
Deviation	Poly	0.0067	0.0037	0.0043	10.3	16.1

Table 1. Summary of electrical measurements made on the test structures (20 samples).



(a) (b)

(c) (d)

Figure 2. Scatter plots of electrical linewidth and sheet resistance for different substrates and nominal track widths. (a) Poly art (100μm), (b) Poly art (300μm), (c) Gloss art (100μm), (d) Gloss art (300μm).

These included two Greek cross structures (arm widths of 100 and 300μm), a box cross, and two linewidth structures (nominal widths of 100 and 300μm). Twenty samples were printed on both polythene and gloss art paper and these were then electrically measured. The cross structure resistivity measurements have been averaged as detailed in reference [1] and the linewidth structures were measured using the procedure outlined in [2]. Table 1 summarises some the measurements from which it can be observed that the printed sheet resistance depends upon the substrate used with the gloss paper resulting in higher resistivities than the poly paper. In addition the measured linewidths are considerably larger than the nominal dimensions given in brackets, indicating ink spread. The standard deviations

Paper type	Nominal track width (μm)	Stdev/mean sheet resistance	Stdev/mean linewidth	Stdev/mean ΔV
Gloss	100	0.103	0.097	0.057
	300	0.073	0.070	0.054
Poly	100	0.073	0.0075	0.034
	300	0.060	0.052	0.049

Table 3. Comparison between the Standard Deviation/Mean for sheet resistance, linewidth and the voltage difference between the taps for both paper types.

of the measurements also indicate that there is a significant variation in both the sheet resistance and linewidth measurements.

The linewidth structure measurement is dependent on the accurate measurement of sheet resistance. For the measurements made on the linewidth structure both the sheet resistance and the linewidth measurements were available for analysis. Table 2 gives the correlation between these two measurements with figure 2 showing the associated scatter plots. It can be observed that, as expected [3], there is a degree of correlation between the measurements.

Paper type	100 μm nominal linewidth	300 μm nominal linewidth
Gloss	0.833	0.689
Poly	0.916	0.640

Table 2. Correlation between the sheet resistance and linewidth extracted from the same cross bridge structure.

To determine how much of the linewidth variation was due to the variability of the sheet resistance measurement the voltage drop between the taps was extracted. The relative variability of the three factors is presented in table 3 and it can be observed that some of the variability of the linewidth measurements is in fact due variation in the extracted value of sheet resistance. This is confirmed by table 4 which shows a much reduced correlation between the sheet resistance measurements and the voltage difference observed between the taps on the linewidth structure.

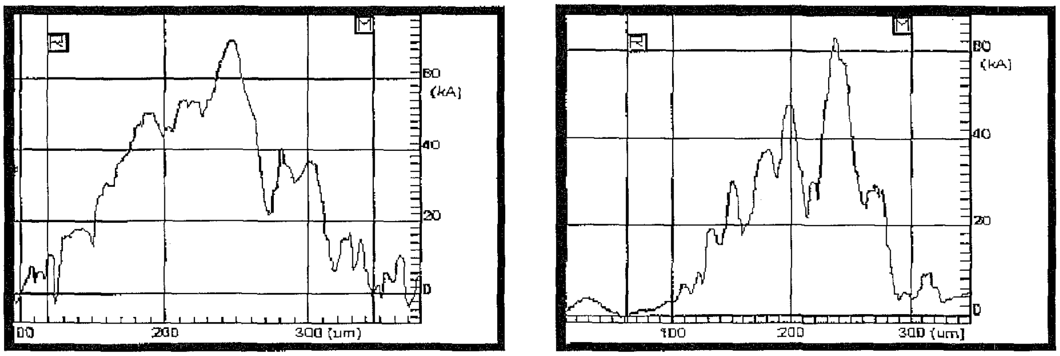
The linewidth and resistivity measurements assume that the film is of uniform thickness and homogeneous. The linewidth extraction also assumes a rectangular cross-section of the track being measured. The film thickness and track cross-section were checked using a Dektak 8000 profilometer and the results for both paper types are shown in figure 3.

Paper type	100 μm nominal linewidth	300 μm nominal linewidth
Gloss	0.401	0.404
Poly	0.199	0.563

Table 4. Correlation between the sheet resistance and the voltage difference between the taps extracted from the same cross bridge structure.

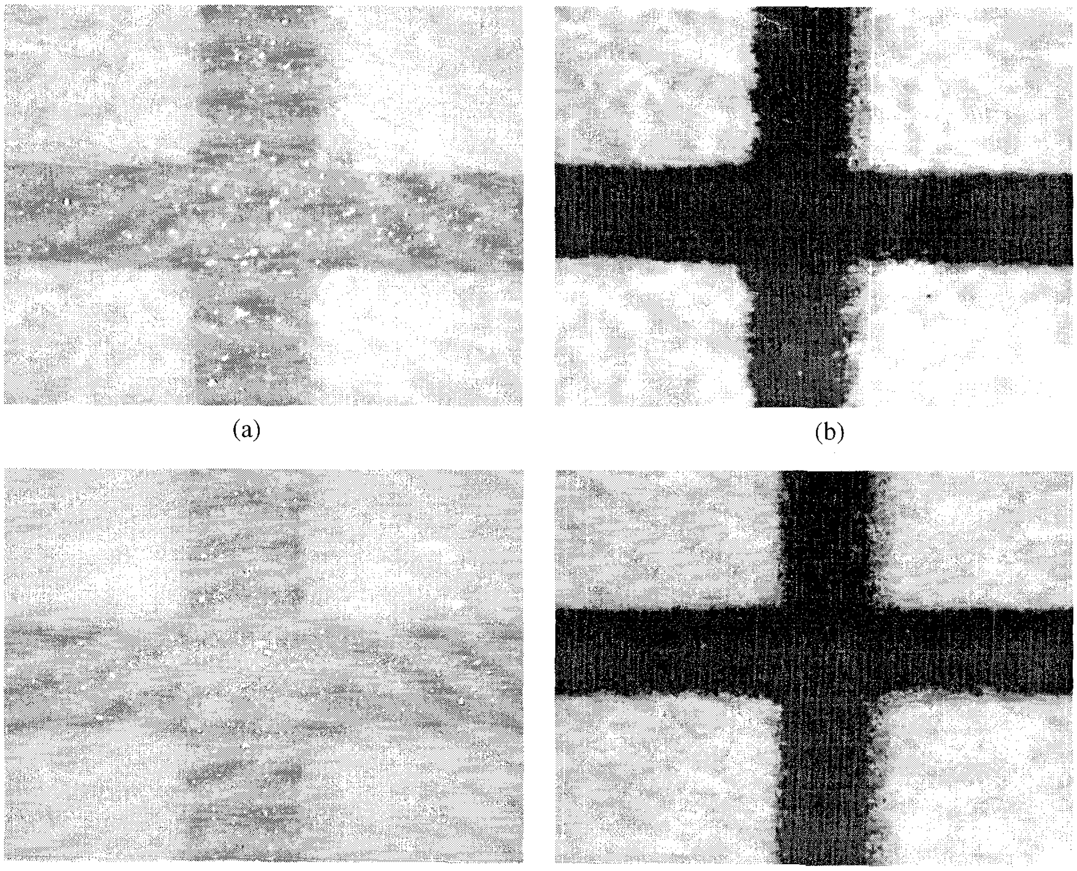
From these results it can be deduced that the tracks appear to be printed with a surface roughness of a few microns resulting in a very non-uniform cross-section. Since these films had not been profiled previously the nature of the cross-section of the track and the degree of surface roughness was neither known nor fully suspected.

The structures were also examined optically to check the electrical linewidth measurements and to determine the edge roughness. Figure 4 shows examples of optical photographs of a Greek cross with 100 μm wide arms in both reflective and transmissive modes for both types of samples. The pictures obtained using reflected light show the granular nature of the surface and, while they do illustrate the roughness of the edge of the tracks, this does not stand out to the same degree as the the pictures taken using transmitted light. These illustrate that the edge acuity is probably a function of the roller direction.



(a) (b)

Figure 3. Example of a surface profile of 100μm track. (a) Poly art, (b) Gloss art.



(a) (b)

(c) (d)

Figure 4. Optical photographs of 100μm crosses. (a) Poly art (reflective), (b) Poly art (transmissive), (c) Gloss art (reflective), (d) Gloss art (transmissive).

The linewidths of the tracks were also measured optically using a Vickers CSS image shearing microscope. This measurement is potentially subjective as the operator effectively determines the edge of tracks. Because the track edge was so rough two measurements were taken. One assumed that all material contributed to the full width of the track while the other measured the minimum width or the "solid" portion of the track.

Substrate		Structure (μm)	Maximum (μm)	Minimum (μm)	Edge roughness (μm)
Poly		(100 μm)	222	178	22 (15)
		(300 μm)	369	417	24 (24)
Gloss		(100 μm)	203	229	13 (18)
		(300 μm)	429	380	24.5 (33)

Table 5. Summary of electrical measurements made on the test structures

Half the difference between the two measurements gives the edge roughness of one side of the track. Example measurements are shown in table 5 and it can be observed that the optically measured track widths are considerably wider than the electrical measurements presented in table 1. This is perhaps not so surprising given the non-rectangular cross-section of the track and the roughness of the track edge.

The edge roughness figures in brackets in table 5 have been derived from the standard deviations presented in table 2. These assume that the edge roughness of both sides of the track is the equivalent of three standard deviations. Hence, the edge roughness of one side of the track is half this value. These results give reasonable agreement with the optical measurements presented in table 5.

One other interesting observation of the optical inspection in transmission mode was the thinness (or lack) of conductor material in the tracks printed on the poly samples. Unfortunately this information is masked on the pictures in figure 2 because of the automatic gain control on the camera used to capture them. Figure 5 gives a better indication of the true situation where the lighter patches indicate very thin or missing material.

Figure 5. Transmissive photo of a horizontal poly track (arrows indicate edge of the track). Light patches indicate thin regions.

3. Conclusions

Microelectronic test structures have been used to help evaluate the new technology of conductive lithographic films. It has been determined that the edge roughness and cross-section of the film affect the electrical measurement of linewidth. In addition the variability of the sheet resistance measurements have been observed to correlate with linewidth measurements. This issue needs further investigation to see whether the variability is due to non-uniformity of the conducting layer caused by the printing process or is related to geometrical variations in the structure [4]. Additionally, a fuller investigation into the most robust cross resistor design for CLFs needs to be undertaken [5].

This work has also highlighted the importance of measuring an accurate value of sheet resistance if linewidth is to be measured [3]. This is especially important if nanometer scale measurements are to be attempted [6].

Electrical measurements have many attractions over the optical ones in that they are performed along the whole length of the track rather than on a very small portion and are also very easily automated. Hence, if the electrical measurement of linewidth can be calibrated to the optical ones then there will be more confidence in using it to both optimise and then control the full production process. However, it should be remembered that it is the electrical performance of the conducting tracks which defines the ultimate performance of the CLFs making the implementation of test structures a necessary part of any process control strategy.

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