Printing of conducting inks on paper

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Abstract

Paper has many attractions as a substrate for the manufacture of flexible electronics, particularly the comparative ease of recycling and recovering the constituents of the inks. However, it is not as smooth as the polymer substrates and also does not normally have sufficient barrier properties for sensitive reactive inks. By careful attention to the coating process a paper has been created that has sufficient smoothness for printing of electronics. As a first stage of the evaluation of this coated stock, a series of trials have been undertaken where appropriate images have been offset printed using a silver conducting ink.

This paper presents an analysis of the images in terms appropriate for the manufacture of electronics. It looks at traditional concepts, such as tone gain, as this affects the minimum printable line. The surface roughness, both of the printed image and the paper, edge straightness, defects (including shorts), the resistance of the lines and the impedance of fine line gaps were measured. These are evaluated through two print runs to provide consistency data as required for the manufacture of electronics.

In the second print run, an overprint was used to increase the film thickness and hence reduce the resistance of the conductors. This highlighted the problems associated with wet on wet printing and the difficulties of obtaining continuity between the two layers.

The results are encouraging and show the potential of paper as a substrate for volume manufacture of disposable electronics.

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1. Introduction

Paper has many attractions as a substrate for the manufacture of flexible electronics, particularly the comparative ease of recycling and recovering the constituents of the inks. However, it is not as smooth as the polymer substrates and also does not normally have sufficient barrier properties for sensitive reactive inks. By careful attention to the coating process a paper has been created that has sufficient smoothness for the printing of electronics. There is significant potential for paper as a substrate for volume manufacture of disposable electronics which could replace some current technologies and open up a number of novel electronic applications.

Currently, printed electronics (as opposed to photo-masked electronic circuits) are predominately produced using the screen printing process. This provides a thick layer of conductive ink (and hence a low resistivity) but is slow (<800 sheets / hour). Using offset lithography would typically increase the speed by an order of magnitude and potentially increase the definition and density of the features being printed, lithography is normally printed at 150 lpi, while this is difficult in screen. Demonstrations of low detail offset printing of paper for the production electronic sensors has already taken place, ref [Neyland et al].

The offset lithography process however has a number of inherent limitations within its normal operational window.

Film thickness : The maximum printed ink film thickness of offset lithography on a paper is typically 3 micron, ref [Kipphan], compared to 20 micron with screen printing. Any reduction in the film thickness results in an increase in a linear electrical resistance which may have a detrimental effect on the electrical properties of the circuit. It increases any power loss in the circuit and also reduces the potential accuracy of an electro – resistive device, e.g. bio sensor, as the track resistance constitutes a greater proportion of the circuit electrical resistance.

Line and feature reproduction : The minimum printable line thickness (in negative and positive) limits the reduction in component size. In graphic image printing, offset lithography typically has significant dot gain (dots appear larger then they should be) as a result of the high impression pressure and porous nature of the paper. This limits the reproduction of fine detailed features, particularly gaps between features. For printed electronics the lines must be as close to that specified as “shorts” must be prevented between adjacent tracks, to maintain electrical continuity and maintain specified track resistances (for a given ink material resistivity). This line reproduction is also affected by the ability of the printing plate to hold the fine line. Although the track resistance is increased by reducing line width there is an opportunity for increased printed feature density, and hence device size.

Surface roughness : The surface roughness of the substrate and ink film play a role in determining the effective printed ink film thickness (and hence resistance) and also plays a part in determining the smallest reproducible feature. The surface finish of the conductive ink layer is also important as other electronic features may be placed, adhered or printed onto the first layer.

Ink electrical resistance : Offset ink is a mixture of particulates and a carrier fluid which cures to form a solid ink film. For a given film thickness, the resistance of a given ink film is limited by amount and properties of the ink film. Increases in conductivity can be obtained by increasing the pigment loading or changing the conductor (e.g. aluminium to silver) in the ink formulation, but these usually have economic and ink rheology limits.

The aims and objectives of the project were to evaluate the above print features and determine the feasibility of the printing electronics to paper via offset lithography.

2. Experimental Method

Trials were carried out on a 6 colour offset press under controlled temperature conditions in a laboratory. The ink used was a prototype ink for offset electronic printing supplied by Flint Ink. The printed image consisted of a standard feature orientated at 4 orthogonal directions. The feature consisted of two tracks of 4 mm length separated by a variable specified gap, Figure 1, rotated at four orthogonal directions to print direction. This facilitated the measurement of total track resistance and the minimum printable gap. The gap was varied from 100 to 5 micron.

The experiment was carried out in two stages. An initial evaluation of this coated paper was undertaken in a printing trial of 2000 sheets where appropriate images using a silver conducting ink. Analysis of these prints was carried out through a print run to provide consistency data as required for the manufacture of electronics. In a second print run, an overprint was used to increase the film thickness and hence reduce the resistance of the conductors .

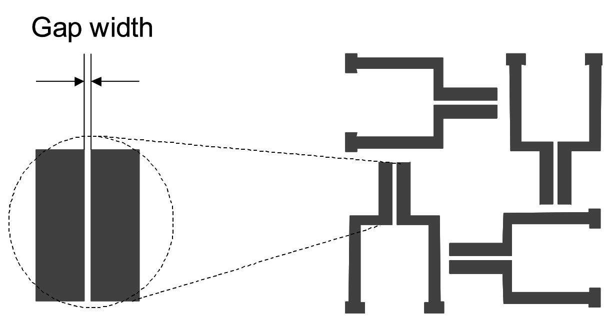


Figure 1 : The generic feature shape printed.

The two layers in the second print run were printed "wet on wet" in accordance with *Figure 2*, where the second layer was printed within the boundaries of the first layer. This improved the ability to hold the narrow gaps between the tracks and to obtain register between successive layers, while maintaining the an increase in total ink film thickness over a large proportion of the conductor's surface.

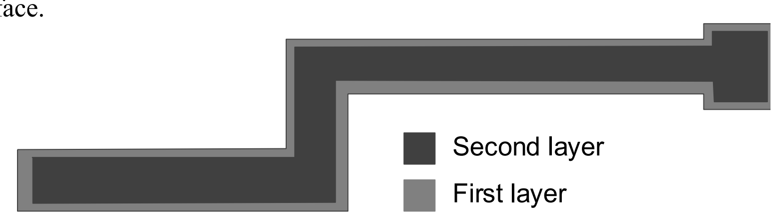


Figure 2 : Second layer print within the first layer boundary.

Images of the geometric shapes were captured using a Leica Wild M32Z microscope, coupled with a Pulnix B&W CCD camera. Measurements were made using the manual and automatic features in a custom print measurement software MicroImage, ref [Jewell, 2004], which produced the gap width average and gap width standard deviation as quality characteristics, ref [Jewell et al 2003].

The thickness of the ink film and the surface roughness were measured using white light interferrometry, ref. [WYKO]. This allows a non contact measurement of all surface topology. The resistance of the conductive tracks was measured using a Fluke series 180 resistance meter.

3. Results

The reproduction of the negative fine line features on the plate was deviated consistently from that specified. There was an average of 60% increase in the line width, Figure 3. Although this change is large, its relative consistency allows further dimensional changes in the printed samples to be attributed to the printing process. With the advent of CTP for plate manufacture, the concept of "relative to film" must be considered and when any printed geometric feature is discussed its size relative to the plate should be the point of reference.

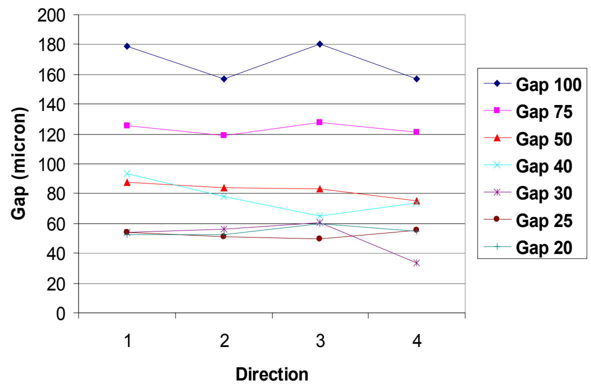


Figure 3 : The dimensional deviation between the gap specified and that measured on the plate.

Optical measurement of the gap between the conductors showed that the printed gap was reduced from that specified and that lines printed in the print direction were consistently wider and rougher, Figure 4.

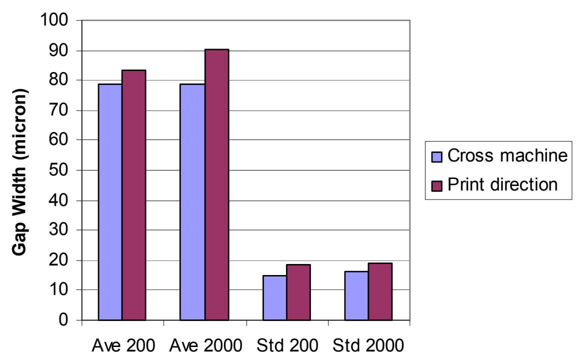


Figure 4: The effect of line orientation on the print width and edge quality for the first and last sampled sheets of the run for the 100 µm gap.

The variation in the gap width was considerable, Figure 5. Although smaller than that specified (particularly in reference to the deviation on the plate), the gap width remained consistent throughout the press run. The minimum consistent printable line width, where the sides of each conductor did not meet (confirmed by resistance measurement, see Figure 9) was around the 75 micron on film which was measured as approximately 58 micron on print. Smaller gaps were visible on the print but were not continuous over the length of the measured gap (approximately 1.9 mm), Figure 6.

Given a standard deviation of approximately 17 micron and assuming a normal distribution in width, then a 3 standard deviation variation tolerance would limit the minimum gap to 50 micron.

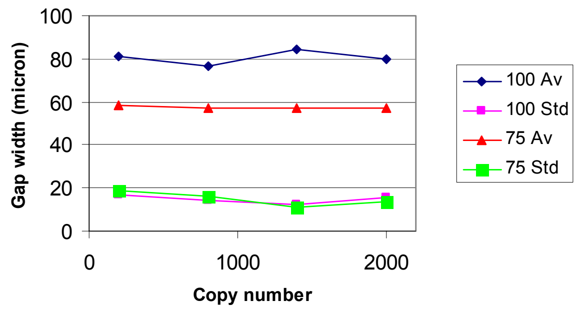
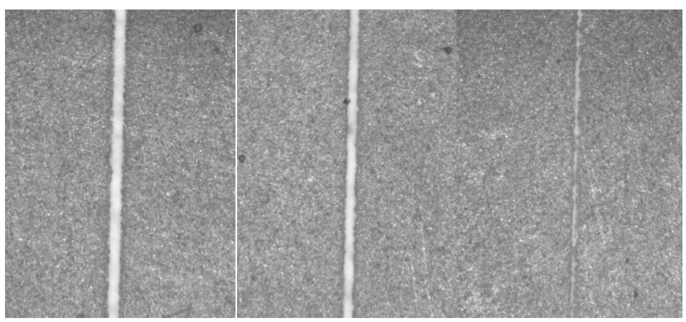


Figure 5 : Gap width and gap width standard deviation through the print run.



100 micron 75 micron 50 micron

Figure 6 : Visual comparison of the gap widths.

The printed ink film thickness was generally less than 1 micron although some areas of print possessed a film thickness over 1 micron, Figure 7.

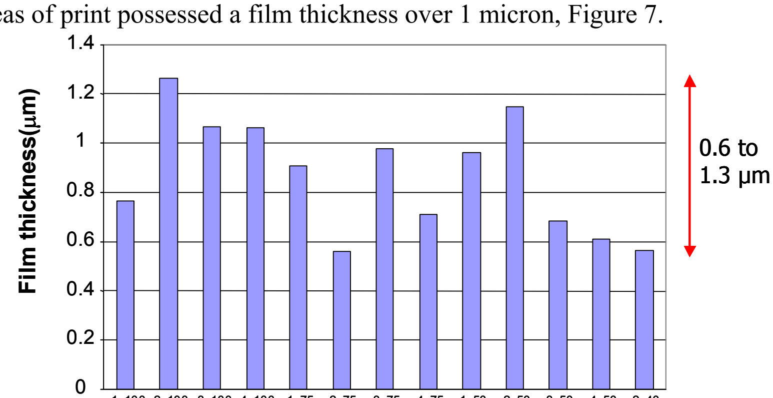


Figure 7 : Cured film thickness measurement for single layer prints.

The deviations between the printed film thickness measurements were associated with the variations in substrate surface, which did not provide an even layer from which a reference could be taken, Figure 8, although the existence of the ink film was clearly visible in the corresponding optical image. The surface roughness of the paper was typically 0.3 µm Ra while a solid region of print was typically 0.46 µm Ra.

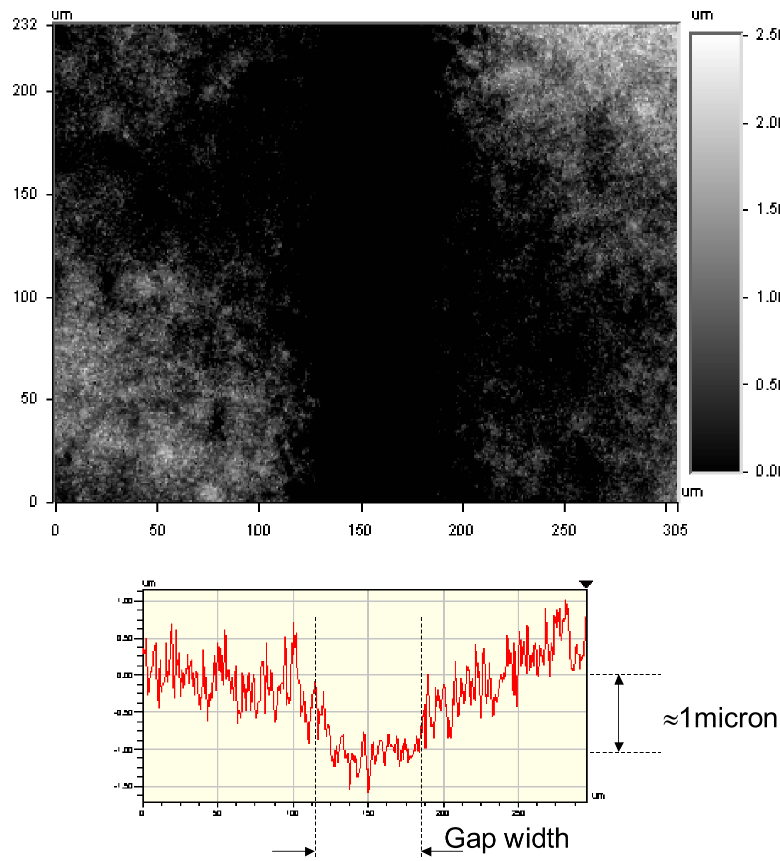


Figure 8: The ink film was barely discernable from the rough substrate using white light inteferrometry although it was clearly visible optically.

The most reliable method for the measuring the ink deposit was the track resistance. This was carried out on all the gap widths allowing the degree of contact between the track sides to be measured. If 100% contact between the ink films is assumed with a 5 micron gap, then any increase in resistance can used to infer the degree of contact between each side of the gap. The track resistance (for a track length of 34.6 mm and 1.5 mm width) reduced during the run from approximately 200 Ω at 200 sheets to 50 Ω at 2000 sheets, Figure 9, indicating an increase in ink deposit through the run.

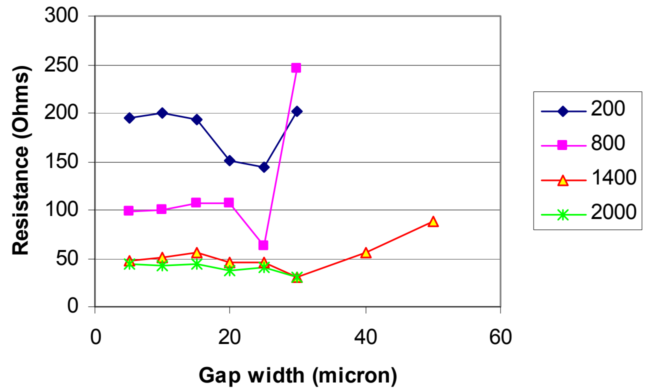


Figure 9 : Resistance through the run for each gap

Increasing the printed film thickness by printing wet on wet had the effect of increasing the resistance of the track, Figure 10. This result may be contrary to that which is expected and will be discussed in the next section of the paper. There is also evidence that the addition of the second ink film reduces minimum printable gap as continuity is maintained between the sides of the gap over a larger range of gap widths. Even with the reduction in second layer feature size so that it lies within the boundaries of the first layer ink fills the gap between the conductors. The difference to the printed ink film thickness by the addition of the 2nd layer was not readily measurable due to the variations in the substrate mentioned previously.

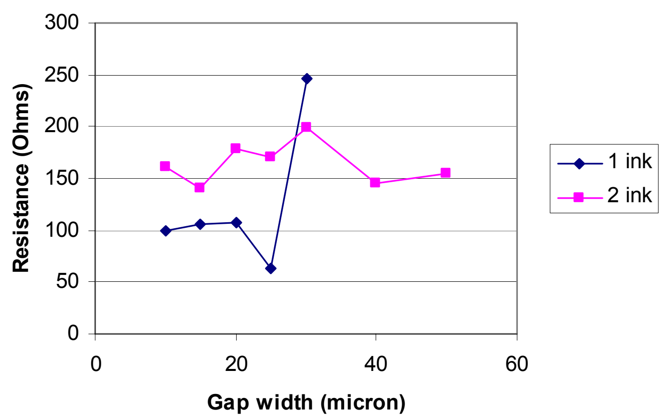


Figure 10 : Printing an additional ink film wet on wet increased the track resistance.

4. Discussion.

There is scope for offset lithography to be used to deposit printed electrical circuits on paper but that the film thickness achieved is less than 1 micron. The increase in track resistance when the second layer is printed may be a result of a number of phenomena.

- Removal of ink from the first printed layer by the second ink application.
- The predominant transfer of the high resistance base at the second ink application.
- A lower transfer of the second ink film which is effectively insulated from the first application.

The resolution obtained in maintaining a consistent 75 micron (printed as 58 micron) gap is certainly an improvement on screen printing, where 100 micron gaps may be printed under controlled conditions. Under optimum conditions, further reductions in the gap between tracks may be possible using offset lithography, allowing smaller device sizes and increased feature density. Given the difference between that specified and that on the plate and the advent of CTP all feature sizes should be related to the print.

In order to reduce the track resistance to something comparable to screen printing, then an increase in the ink conductivity will be required. This is limited by the particulate loading that can be included in any ink formulation. However, there are many applications where the increased resistance may not be a critical, e.g. field effect devices such as electro luminescent lamps, or may be beneficial, e.g. for micro heaters, then offset lithography provides a cheap method micro fabrication.

5. Conclusions

There is scope for using offset lithography to paper for the disposable electronic production. A summary of the main conclusions of the current work are :

- Over a production run of 2000 prints, the lithographic process was capable of maintaining printable gap.
- Typically a 100 micron gap can be guaranteed between adjacent conductors on this paper.
- Printing wet on wet does not reduce the resistance of a track. Several possible theories have been put forward for this
- Its low film weight and high resistance does not allow it directly compete with screen printing but a number of applications.

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