# Evaluation of Gravure for Printed Electronics

Erika Hrehorova[*], Alexandra Pekarovicova[*], and Paul D. Fleming[*]

## Keywords

Gravure, Printed Electronics, Conductive Ink, White Light Interferometry,
Printed Lines Directionality

## Abstract

This work focuses on evaluation of engraving quality and printability of conductive traces by gravure printing for use in printed electronics. Gravure print forms were prepared by chemical etching, which nowadays uses laser ablation of the mask resist. The quality of engraved features was characterized with white light interferometry. Various line widths at five different angles to print direction were studied and it was observed that the actual engraved line widths are higher than specified. This widening effect was observed for all measured line widths and angles to imaging direction.

In order to evaluate the quality of printed fine lines for applications in printed electronics, silver-flake conductive ink was used to print from these characterized engraved forms. It was observed that lines oriented perpendicularly to print direction were printed wider than the lines in parallel with print direction. Moreover, the quality of printed lines was evaluated in terms of line width standard deviation and it was found that lines printed parallel to the print direction have the lowest edge raggedness (lowest standard deviation of line width).

---

[*] Department of Paper Engineering, Chemical Engineering, and Imaging, Western Michigan University, Kalamazoo, MI

# Introduction

Two major application categories for printed electronics in the next 20 years include i) display and lighting applications and ii) memory and logic circuits (Harrop, 2005). The top five more specific product areas for printed electronics, representing about 79% of market share in the next five years are RFID tags, displays, photovoltaics, electronic signage, and backplanes (Gasman, 2008). Among conventional printing processes, gravure printing is the premier process for printed electronics, due to its very high quality and ability to print at very high speeds. Robustness of its image carrier is advantageous, contributing to very good printing stability over time. These advantages of gravure printing make it a very promising process for electronics fabrication (Pudas, 2005, Fenoll, 2005).

The first step in evaluation of gravure printing as a platform for electronics manufacture is to determine the capability and limits of available engraving methods. High quality engraving of basic electronic components and features is crucial in the production of functional electronic devices. The simplest feature to be considered is a line. Various lines can function as interconnects between active blocks of integrated circuits or as contact electrodes for individual transistors. Requirements for line dimensions (such as width and length) as well as line spacing (gaps) used in integrated circuits are many times very strict. In order to increase the performance of printed integrated circuits the active channels between source and drain electrodes in transistor structures should be very small. These parameters are affected by engraving method, ink and substrate properties, as well as process parameters.

There are several different engraving methods available and used in the gravure industry. Each of these methods produces different sizes and shapes of engraved cells, which influence the ink release. Resolution, determining the line width, is limited by the engraving process used. Among engraving methods, electromechanical engraving is the most widely used for publication or packaging gravure products. It uses a diamond stylus, which cuts gravure cells into the copper surface. Ragged edges are very common with this type of engraving, however there was much improvement done with smoothening of the edges. For printed electronics, however, so called indirect laser engraving is the most promising because of the possibility to engrave smooth edges and lines as continuous grooves. As opposed to direct laser engraving, where laser beams directly ablate the cylinder surface to produce gravure cells, in indirect laser engraving, the laser beam is employed to ablate the mask resist. Subsequently, only ablated areas are exposed and come in contact with the etchant solution. The cell depth is controlled by the etching time, concentration and temperature of etchant solution. Thus such produced cells typically have the same depth and tones are controlled only by cell opening (Henning, 2006). The typical workflow of gravure cylinder preparation using laser ablation followed by chemical etching is shown on the Figure 1. The resolution of engraving is limited by the diameter of the laser beam focus. With direct laser imaging system, a minimum beam size of about 40 μm is employed and therefore the minimum line width is about 40 μm. Indirect laser systems use a laser beam split into four beams of equal power (sufficient to ablate the mask resist) and thus it typically works with a beam diameter of 10 - 20 μm for gravure applications (Siegenthaler, 2004). The minimum line width is therefore also about 10 - 20 μm, or a little more due to the sidewall etching.

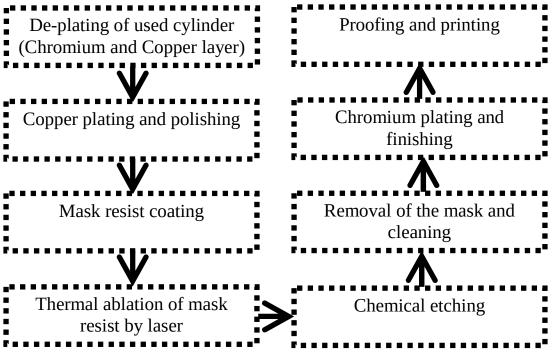


*Figure 1: Manufacturing steps involved in gravure cylinder preparation by digital laser imaging followed by chemical etching.*

## Materials and Experimental Methods

### *Print Form Design and Engraving*

Design of the print form included larger solid areas to evaluate the cell dimensions uniformity and various line blocks at five different angles to the print direction. Line blocks incorporated into the design were designed in such a way, so that the widest specified lines (300 μm) were at the edges and the narrowest lines (15 μm) are in the center. Figure 2 illustrates different positions of line blocks with regard to the print direction. The red boxes in Figure 2 demonstrate areas where the images for engraving and printing quality were taken.

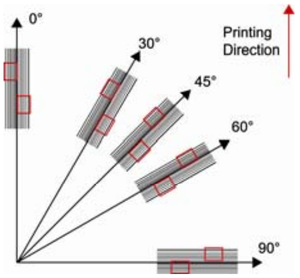


*Figure 2: Line blocks of different line widths and at different angles to the print direction*

Gravure print forms for this work were engraved by Schepers GmbH & Co. KG, Germany, using laser imaging of the mask resist followed by chemical etching as described in the introduction. After engraving, the cylinder was chromium plated and polished by traditional procedures.

### *Evaluation of Engraving Quality*

There are several different methods to characterize and evaluate the quality of engraving. These include optical microscopy, fluid volumetrics, confocal microscopy and white light interferometry or replica (Bohan, 2001). In this work white light interferometry in vertical scanning mode was used (WYKO RST-Plus vertical interference microscope). This method has already shown its applicability in the printing industry, more specifically in measuring of anilox rolls for flexographic printing (Caber, 1993), engraved cells for gravure (Bohan, 2001) as well as screen printed lines and patterns (Jewel, 2005).

The principle of white light interferometry is based on the splitting the beam of polychromatic white light into two parts, whereas one part travels to a reference mirror and the other to the surface under study. Interference fringes are observed when the light reflected from the sample recombines with the light reflected from the reference mirror, where the best-contrast fringes occur at the best focus. In vertical scanning mode, the interferometric lens scans the surface at varying heights by vertical movement through the focus and capturing frames of interference data at fixed intervals. Thus it is possible to obtain the height profile of a tested surface (Veeco, 1999).

### *Printing and Evaluation of Print Quality*

A K Printing Proofer (RK Print-Coat Instruments Limited) in gravure mode was employed in this study. Silver-flake conductive ink was used to print on commercially available label stock paper. Print quality was evaluated using image analysis system ImageXpert (KDY Inc.) comprised of a motion table for sample positioning, two calibrated cameras for image capture and ImageXpert image analysis software (IX 10.0b63). Some components of line quality include average line width, standard deviation of line width variation, edge raggedness and line sharpness (Wolin, 1998). In this work, average line width and standard deviation of line width is reported for lines printed at five different angles to the print direction.

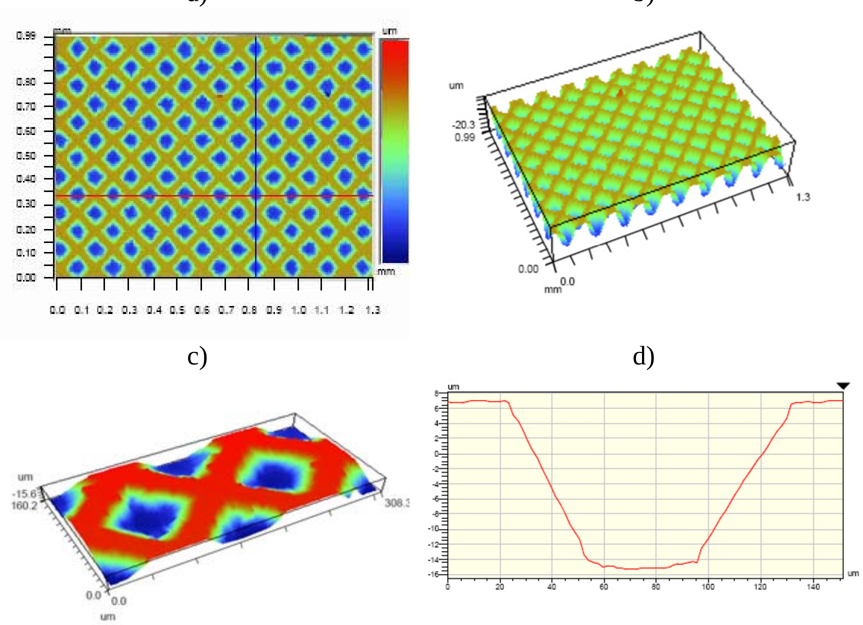
## Results and Discussion

### *Evaluation of Engraving Quality*

With white light interferometry, it is possible to obtain accurate 2D and 3D profiles of engraved forms. Typical results from vertical scanning are presented in Figure 3a and 3b. In order to extract the actual dimensions of engraved cells and analyze their uniformity, X- and Y- cross-sections were made across multiple cells and rows of cells. For better illustration, a detailed image of gravure cells, showing shapes in 3D perspective and in cross-section, is given in

Figure 3c and 3d. The average depth of the cell extracted from both, X-profile and Y-profiles, was found to be 21.6 ± 0.35 µm. The diagonal dimensions for measured cells calculated from X- and Y- cross-sections are very similar, implying the square shape of engraved cells on the top surface. The diagonal length was measured to be 100.2 ± 3.6 µm as measured from X – cross-section and 102.6 ± 2.4 µm from Y – cross-section.

a) b)



c) d)

*Figure 3: 2D contour (a) and 3D profiles (b) of solid coverage area and detailed image of engraved cells showing the shape in 3D perspective (c) and in cross-section (d)*

When calculating dimensions using pixel data from the VSI scans, one must take into account the roughness of chromium surfaces, which can lead to variations when defining the cell dimensions (Bohan, 2001). Figure 4 shows the surface roughness of a chromium layer, with visible polishing marks. Surface characteristics of measured chromium layer of gravure print form are as follows: average roughness $R_a$ = 92 nm, root mean square (RMS) roughness $R_q$ = 115 nm, average maximum peak-to-valley height $R_z$ = 836 nm and maximum peak-to-valley height $R_t$ = 1.2 µm. In gravure printing, it is typical that a chromium layer has so called cracks, providing a beneficial lubrication for the doctor blade (Gillett, 2003). However, there are no reports to date on the effects of cracks in chromium on printing of functional materials. In this work, the top surface height mean was used in calculation of cell parameters.

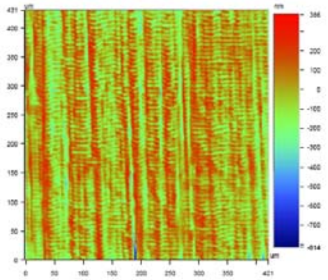


*Figure 4: Illustration of surface roughness of chromium layer*

Traditionally in gravure printing, the image is broken down to individual cells with dimensions (cell opening and depth) according to desired tone value. Fine text and lines are typically engraved as rows of discrete dots and thus ink spreading is essential in order to form a continuous line. With indirect laser engraving method, it is possible to engrave line edges and fine lines as continuous grooves, which might lead to increased uniformity of the printed line width and thus reduced edge roughness. However, the uniformity of width and depth along the groove is essential in order to assure consistent amount of ink being deposited onto the substrate.

In this work, line widths ranging from 15 to 300 μm and positioned at different angles to printed direction were evaluated. The width of engraved lines was measured and plotted against line width specified in the digital file that was sent to the imaging system. A linear function ($y = a + b*x$) was used to fit the plots to determine the intercept and slope for each tested angle relative to the print direction. Figure 5 shows the linear fit for lines engraved parallel to the print direction.

Table 1 summarizes the parameters of linear fits, for lines oriented at different angles relative to print direction. Error for these parameters was calculated from standard deviations for individual measurements of line widths. $R^2$ values in Table 1 shows that measured data fit the linear function very well. The slope indicates how steep the linear relationship between variables is and it can be seen that the value is very close for all tested angles. Intercept values indicate how much gain in line width can be expected during the engraving process. According to the results, the lowest width gain was found for the parallel direction, although the differences between angles are probably not significant, being within the standard deviation of the measurement. There are several possible causes of such widening effects during the engraving process. These may include the scattering of the laser beam during laser ablation of the mask resist and sidewall etching. In order to determine the widening effects of individual processes involved in gravure cylinder engraving, further study is necessary.

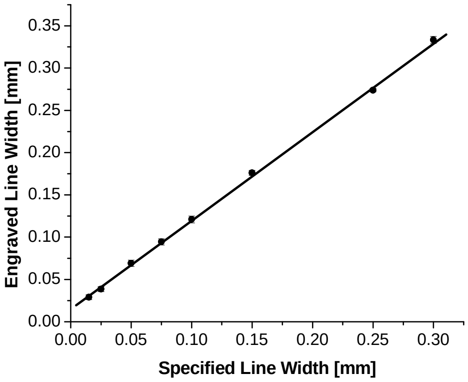


*Figure 5: Linear fit for engraved vs. specified line width for lines in print direction*

*Table 1: Parameters of linear fit (y = a + b*x) for engraved line widths at different angles relative to print direction*

| **Angle [deg]** | **a [mm]** | **b** | **$R^2$** |
|---|---|---|---|
| 0 | 0.014 ± 0.002 | 1.047 ± 0.011 | 0.999 |
| 30 | 0.017 ± 0.001 | 1.070 ± 0.011 | 0.999 |
| 45 | 0.019 ± 0.002 | 1.068 ± 0.010 | 0.999 |
| 60 | 0.019 ± 0.002 | 1.080 ± 0.008 | 0.999 |
| 90 | 0.017 ± 0.001 | 1.065 ± 0.008 | 0.999 |

It should be noticed that the issue of line widening is more pronounced for very fine lines (sub 100 μm line widths). For example, the specified line width of 15 μm was measured to be 29 ± 3 μm in parallel and 32 ± 2 μm in perpendicular directions. This corresponds to the average width gain of 94% and 111% for parallel and perpendicular direction, respectively. This needs to be taken into consideration when designing different functional layers of features for electronics. Widening of engraved lines consequently leads to reducing the distance (gap) between designed lines. As an example, let us consider the interdigitated electrodes design for source and drain electrodes of printed transistor (Figure 6). The electrode width in Figure 6 was specified to be 50 μm and the distance between electrodes 100 μm. The engraved electrode width was measured to be 68 ± 4 μm. At the same time, the gap between electrodes reduces and it was measured to be 85 ± 3 μm. When considering printing of source and drain electrodes for transistor structures, it is desirable to have very small distance between them, because the performance of a transistor increases with decreasing the distance that the charge carriers need to travel (Dimitrakopoulos, 2001).

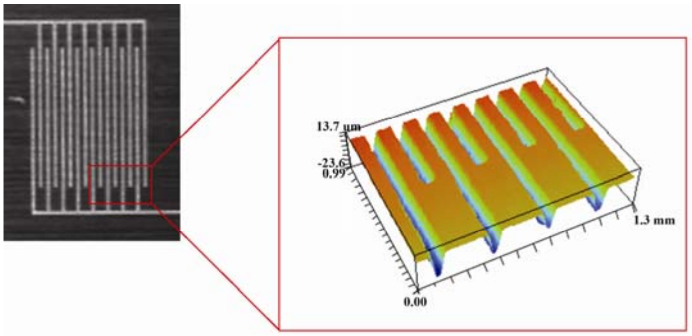


*Figure 6: Engraved interdigitated source and drain electrodes design for printed transistor*

### *Evaluation of Print Quality*

In traditional gravure printing, the smoothest edges are typically produced in the print direction. Printing in the perpendicular direction often results in more pronounced “sawtooth” edges, poor line contours and narrower line widths. This was reported for lines printed using graphic ink and gravure cylinder engraved by electromechanical engraving (Jewel, 2006). However, the situation might be different when printing from continuous grooves. It has been reported that strong eddy currents can be observed when the substrate comes in contact with the fluid in the groove and, as the substrate exits the groove, a recirculation region attaches to the moving substrate and follows it (Yin, 2006). This leads to printing lines oriented perpendicularly to print direction being wider than in the parallel direction. It was also reported that the strength of recirculation depends on the groove orientation relative to the print direction. As the angle increases from 0° to 90°, the strength of recirculation also increases (Yin, 2003).

Silver-flake conductive ink was printed using a gravure K-printing proofer to evaluate the quality of printed lines. Similarly to the engraved lines evaluation, the width of printed lines was plotted against line width specified in the digital file sent to the imaging system and fitted using a linear function ($y = a + b*x$) to determine intercept and slope for each tested angle relative to the print direction. Line width evaluated range was from 75 to 300 µm, due to line widening issues, as it will be discussed further. Figure 7a shows an example of the linear fits for lines printed in parallel and perpendicular directions, and it is clear that lines printed in the perpendicular direction are wider that those in the parallel direction. This can be also seen in Figure 7b showing the 150 µm nominal line with measured line width of 211 ± 12 µm and 288 ± 23 µm in parallel and perpendicular directions, respectively. Table 2 shows parameters of linear fits for lines printed at all tested angles.

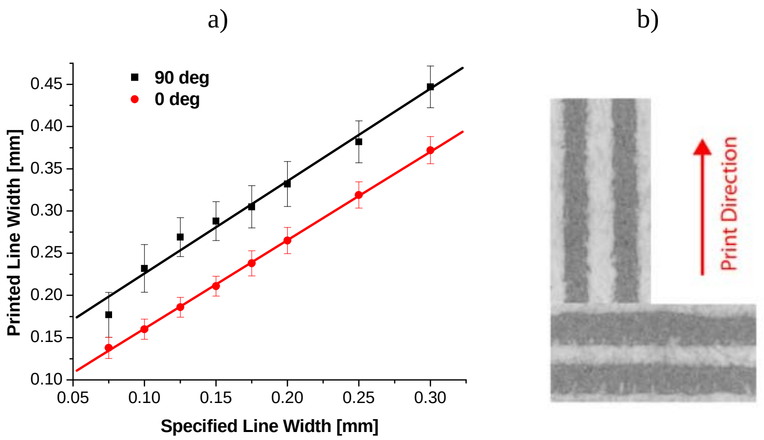


*Figure 7:* a) *Linear fit for printed vs. specified line width for lines and b) illustration of printed 150 μm specified line in print (0 deg) and cross-print (90 deg) direction*

*Table 2: Parameters of linear fit (y = a + b*x) for printed line widths at different angles relative to print direction*

| **Angle [deg]** | **a [mm]** | **b** | **$R^2$** |
|---|---|---|---|
| 0 | 0.056 ± 0.012 | 1.048 ± 0.071 | 0.999 |
| 30 | 0.083 ± 0.021 | 1.021 ± 0.116 | 0.998 |
| 45 | 0.086 ± 0.021 | 1.019 ± 0.114 | 0.993 |
| 60 | 0.097 ± 0.022 | 0.998 ± 0.123 | 0.998 |
| 90 | 0.117 ± 0.024 | 1.094 ± 0.127 | 0.991 |

It can be seen from Table 2 that with increasing angle, the average intercept value also increases. Although, it should be noticed that the errors for parameters of the linear fits are quite high and the differences between some angles are not significant. Figure 8 compares the linear fit parameters for both engraved and printed lines. The slope values are similar for engraved and printed lines, being 1.0 within the standard deviation of the measurements. Error bars for printed lines are higher than for engraved lines, due to higher non-uniformity of printed lines. Considering the intercept values, it can be seen that the width gain coming from widening of the lines during printing is more significant that from engraving process. It was already shown that during the engraving process, parallel lines can gain about 14 ± 2 μm in their width. However, during printing, the line width is increased further and the final width gain comes down to 56 ± 12 μm compared to specified line width. For perpendicular lines, there is a difference of about 100 μm in line width between engraved and printed lines.

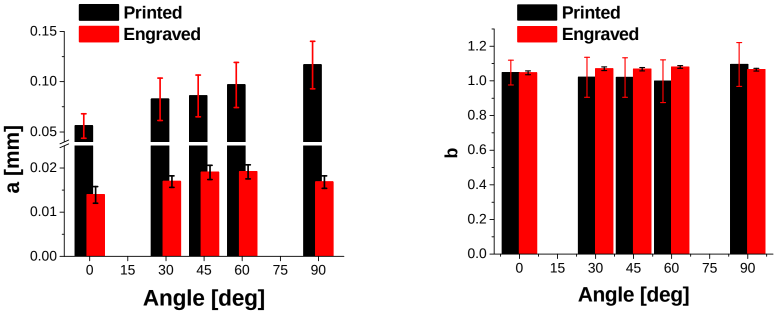


*Figure 8: Comparison of linear fit (y = a + b*x) parameters for engraved and printed lines at different angles to print direction.*

The standard deviation of line width was considered separately as a measure of line definition and thus the higher the standard deviation, the less uniform the line edge. Figure 9 shows the standard deviation at all tested angles calculated as the arithmetic average among tested line widths. The lowest deviation was found for the parallel direction and it can be seen that, as the line orientation deviates from print direction, uniformity of the line width reduces. This can be also seen in Figure 7b.

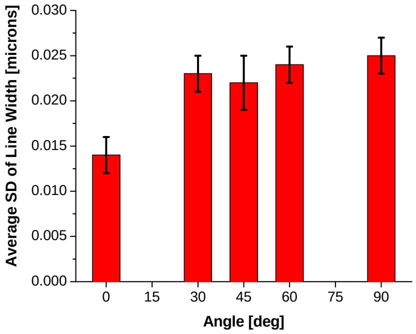


*Figure 9: Average standard deviation of line width for tested angles*

Consider the same design of interdigitated source and drain electrodes for a printed transistor (Figure 6), which has the electrodes width and the gap between electrodes designed as 50 and 100 μm, respectively. As it was shown earlier for parallel direction, there is about 56 μm gain in width during printing and thus it can be expected that the gap between electrodes will be filled causing the short circuit. Therefore it is very important to consider these widening effects during engraving and printing when designing circuit components.

It should also be noticed that this work evaluates printing of conductive traces only with one type of silver-flake conductive ink on selected paper substrate using particular press and process parameters. Very likely, the results reported here will not be the same for different inks and substrates combinations or printing settings. The widening of printed lines depends on many factors, such as ink rheology and surface tension, substrate properties, printing speed, etc. It was reported that conductive polymer ink having lower viscosity produces wider lines that those reported here (Hrehorova, 2007). Moreover, line uniformity can be improved by using smaller size of silver particles. It was found that conductive ink based on silver nanoparticles produce smoother edges, as well as lower width gain when compared to silver-flake ink used in this work (Hrehorova, 2008).

## Conclusions

Printing with graphic inks has been around for many years and it is very well optimized to the requirements for applications in reproduction of visual images. Recent efforts are pushing toward the use of printing technologies as a manufacturing platform for electronics production. The potential of different printing technologies is yet very often not known. Several challenging issues must be overcome for successful incorporation of printing to electronics manufacture, such as resolution, accuracy (registration tolerances), continuity and uniformity of the printed layers.

This work focuses on the evaluation of gravure printing for printing of conductive traces. A print form was engraved using the indirect laser method. The quality of engraved print form was studied using white light interferometry. The engraved line width was studied for a range of line widths at five different orientations with regard to print directions. It was found that the width of engraved lines is higher than the line widths specified in electronic file sent to the laser imaging system. Measurements of engraved line width were plotted and a linear function was used to calculate the relationship between specified and the actual engraved line widths. The differences in engraved line widths at various angles were minimal. However, when considering printing from engraved grooves, the directionality of gravure printing is more pronounced and needs to be taken into account when printing features needed in electronic components. Silver-flake conductive ink was used to evaluate quality of gravure printed traces. It was found that lines in perpendicular direction were printed wider that those in parallel with the print direction. Moreover, lines in print direction were printed more uniformly.

## Acknowledgements

Authors would like to thank Mr. Walter Siegenthaler, Max Daetwyler Corp. for engraving of print forms used in this work. Thanks also go to 21st Centrury Jobs Fund and Michigan Economical Development Corporation for financial support.

# Literature Cited

Bohan, M. F. J., Clist A. M., Claypole T. C., Gethin D. T.
2001 “Characterisation of gravure cylinders,” Proc. of TAGA’s 53rd Annual Technical Conference

Caber, P. J.
1993 “Interferometric profiler for rough surfaces,” Applied Optics, 32, 19, p. 3438-3441

Dimitrakopoulos, C. D., Mascaro, D. J.
2001 “Organic thin-film transistors: A review of recent advances,” IBM J. Res. & Dev., Vol. 45, No. 1, p. 11-27

Fenoll, M., Catusse, R., Rousset, E.
2005 “Gravure Printing: Material Characterization for All-Organic Capacitor,” Proc. of IARIGAI’s 32nd International Research Conference on Digitalization and Print Media, p. 83 – 92

Gasman L.
2008 “Flexible Electronics: Capacity and Investment Forecast”, USDC Flexible Display Conference, Phoenix, AZ, January 21-24

Gillett, K. et al.
2003 “Gravure – Process and Technology,” GAA and GEF, Rochester, 2nd Edition, NY

Harrop, P., Das, R.
2005 “Organic Electronics Forecasts, Players, Opportunities 2005-2025”, IDTechEx Press

Henning G., Selbmann K. H., Brocklet A.
2006 “Laser Engraving in Gravure Industry,” Proc. of SPIE: Workshop on Laser Applications in Europe, 6157, 61570C

Hrehorova, E.
2007 “Materials and Processes for Printed Electronics: Evaluation of Gravure Printing in Electronics Manufacture” PhD Dissertation, Western Michigan University, June 2007, p. 123-125

Hrehorova, E.
2008, unpublished results

Jewell, E. H., Claypole, T. C., Gethin, D. T.
2005 “Two- and Three-Dimensional characterization of Screen-Printed Lines,” Proc. of TAGA’s 57th Annual Technical Conference

Jewell, E. H., Claypole, T. C., Davies, G. R.
2006 “Print Line Quality in the Gravure Process,” Proc. of TAGA’s 58th Annual Technical Conference

Pudas, M., Halonen, N., Granat, P., Vahakangas, J.
2005 “Gravure Printing of Conductive Particulate Polymer Inks on Flexible Substrates,” Prog. Org. Coat., 54, p. 310 - 316

Siegenthaler, W.
2004 “Lasers in Engraving,” Gravure Cylinder User Group, March 30 – April 1, Nashville, Tennessee

Veeco Metrology Group
1999 “WYKO Profilers - Technical Reference Manual,”

Wolin, D., Johnson, K., Kipman Y.
1998 “The Importance of Objective Analysis in Image Quality Evaluation,“ Proc. of IS&Ts NIP 14: International Conference on Digital Printing Technologies, p. 603-606

Yin, X., Kumar, S.
2003 “Flow visualization studies in scaled-up gravure grooves and cells”, Proc. of TAGA’s 55th Annual Technical Conference, p. 540-545

Yin, X., Kumar, S.
2006 “Flow visualization of the liquid emptying process in scaled-up gravure grooves and cells”, Chem. Eng. Sc., 61, 4, p. 1146-1156