Suitability of Gravure Printing for High Volume Fabrication of Electronics

Erika Hrehorova, Marian Rebros, Alexandra Pekarovicova and Paul D. Fleming,
Department of Paper Engineering, Chemical Engineering and Imaging, Western Michigan University, Kalamazoo, MI

Abstract

This paper considers gravure printing and its suitability for application in electronics fabrication. Current applications of gravure in printed electronics are reviewed. Various aspects of gravure printing are discussed, such as preparation of gravure cylinders, engraving quality and the effect of engraving parameters on print quality. It is shown that engraving resolution and depth of engraved cells have an impact on the quality of printed layers. Gravure printing of fine features required for printed electronic devices is also evaluated.

Introduction

Various printing technologies are being tested for their suitability in electronics fabrication. Present and future applications of printed electronics include printed wiring boards (PWB), membrane touches, radio-frequency identification (RFID) tags, organic light emitting diodes (OLEDs) for display and lighting applications, e-paper, active matrix (AM) or passive matrix (PM) display backplanes, batteries, solar cells and various sensors[1]. The material and resolution requirements differ based on applications. Thicker functional layers are required for RFID antennae and batteries. On the other side, very thin and uniform layers are necessary for transistors, displays and solar cells. Considering the resolution, energy applications, like solar cells and batteries, are more tolerant to lower resolutions than transistors or displays [2], where very fine features and precise overprinting of functional layers is crucial for required performance.

Inkjet printing has been used by many research groups to deposit functional materials for various applications. It is a very quick and versatile printing method for evaluation of materials and their compatibility with the substrate or underlying layers. Inkjet has its advantages over conventional printing methods, when it comes to prototyping and laboratory scale research. It typically requires small amounts of material and it eliminates the cost and time for preparation of an image carrier. However, when it comes to high volume and roll-to-roll production, conventional high speed, high volume printing processes, like gravure, flexography or offset printing, would be more suitable. These processes have been very well optimized for visual printing, but when it comes to printing of non-traditional materials, each of them has its limitations. In traditional printing, it is typical that the ink formulation is greatly determined by the printing process. In printed electronics, however, it is not unusual that the deposition (printing) method is rather determined by limited processability and solubility of some functional materials. In flexography, photopolymer plates are typically not compatible with aromatic and aliphatic hydrocarbons often used for solution processing of conductive or semiconductive polymers. Flexographic plates tend to swell and distort upon prolonged contact with such solvents [3] and thus new, more resistant, plate materials would be needed. Similarly in offset printing, elastomers used for inking rollers and blankets prevent use of strong solvents that could soften and swell them [4]. Considering, materials compatibility, gravure printing is probably the most resistant to strong solvents, although materials should meet other requirements, like good lubricity, low abrasion and low corrosivity, to enhance doctor blade and cylinder life, especially with high volume printing [5]. In addition, gravure printing is capable of the highest printing speed among traditional printing processes, very high quality and stability over time, which makes it very attractive for printed electronics.

Gravure Printing and its Role in Printed Electronics

Traditionally, gravure printing is used for printing catalogues and magazines, cigarette labels, food and cosmetic packaging, décor, stamps and security printing, etc. Gravure printing is mechanically simpler when compared to the other printing processes. It can print on a broad range of substrates and the widest range of ink formulations can be applied. A gravure printing unit consists of i) engraved cylinder rotating in inking pan, ii) doctor blade wiping the ink from non-image areas, iii) impression roller, which brings the substrate into contact with the cylinder and helps transfer the image and iv) a dryer [5]. The illustration of gravure printing nip is shown in the **Figure 1**. There are many factors influencing gravure print quality [6]. These include substrate properties (smoothness, compressibility, porosity and ink receptivity, wettability, etc.) and ink properties (ink chemistry, viscosity, rheological behavior, solvent evaporation rate and drying, etc.). Furthermore, process parameters, such as doctor blade angle and pressure, impression pressure and speed, have tremendous effects on quality of printed ink films. Very important is also the preparation of the image carrier by different engraving methods, because ink release from engraved cells will depend on the width and depth of cells and their overall shape. Some of the factors influencing the quality of gravure printed features and layers will be discussed later in this work.

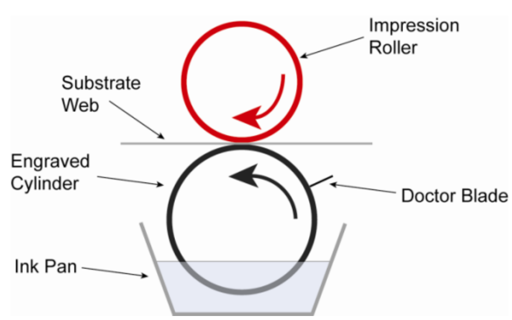

Figure 1 *Schematic illustration of gravure printing unit*

Gravure printing is already being used for some of the printed electronics applications for deposition of at least one functional layer. Antennae for UHF (ultra-high frequency) RFID tags were successfully printed by gravure using silver flake conductive ink directly on packaging materials and their performance was approaching traditional copper etched antenna [7]. Gravure was shown to be feasible in fabrication of OLEDs [8] and it was shown that both inorganic and organic layers can be deposited with high uniformity over a large area by optimization of printing parameters and ink properties. Transparent ITO (indium tin oxide) patterns can be gravure printed for applications such as displays, solar cells or sensors by using ITO nanoparticles inks [9]. Other functional inks based on conductive polymers [10,11], light-emitting polymers [8] and dielectrics [12] are being formulated to meet the requirements of gravure printing.

Gravure Printing Parameters and Print Quality

Engraving Parameters

The heart of the gravure press is the engraved cylinder. Renewed interest in gravure printing is driving the improvements in the quality of gravure cylinder engraving, resolution and registration, far beyond the requirements of a human eye [13]. High quality engraving of basic electronic components and features is crucial in the production of functional electronic devices. Requirements for line dimensions and line spacing used for contact electrodes in integrated circuits are many times very strict.

Traditionally in gravure printing, the image is broken down to individual cells. 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. Electromechanical engraving is the most common method in gravure cylinder imaging. However, due to the nature of this process, poor line definition characterized by ragged edges (also known as saw-tooth edges) is very common. Many improvements in the quality of engraving have been made by using laser technologies, which offers much higher resolutions and smoother edges than normally possible with electromechanical engraving. The resolution of engraving is limited by the diameter of the laser beam focus. With direct laser engraving, where gravure cells are produced by local evaporation of metal (typically zinc), a minimum beam size of about 40 µm is used and therefore the minimum line width is about 40 µm. Although, there have been advances made in laser imaging and now it is possible to use high power fiber lasers with 10-15 µm focus diameter to engrave various surfaces like zinc, ceramic or copper at resolutions up to 2000 lines/cm [14]. Another application of laser technology in gravure cylinder preparation is in so-called indirect laser engraving. The laser beam can be used to ablate a mask resist, which is coated onto the copper plated cylinder. Ablated areas are then chemically etched away to produce engraved image. The cell depth is controlled by the time of etching and thus such produced cells typically have the same depth and tones are controlled only by cell opening [15]. A highly precise fiber laser with the focus point diameter of 10 µm is nowadays used to produce the finest details [16].

Resolution of engraving plays the crucial role in resulting print quality. Diameter of gravure cells is defined by screen resolution and in visual printing it typically ranges from 25 to 150 µm. Cell depths, typically 1 to 40 µm, defines optical density of printed dots [14] or in other words the thickness of printed ink film. **Figure 2** shows typical gravure cells as engraved at three different resolutions by using indirect laser technology.

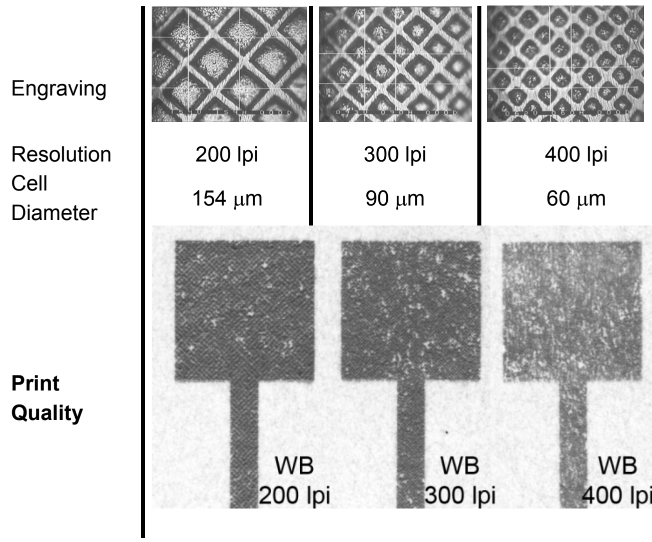

***Figure 2** Gravure cells engraved using indirect laser engraving with different resolutions and corresponding print quality of silver flake conductive ink gravure printed on label paper. Cell depth is 20 µm for all resolutions, WB stands for water based silver flake conductive ink*

Cell dimensions together with ink rheology greatly determine the ink release. It has been reported that with increasing the size of the gravure cell, the degree of ink transfer also increases [17]. It is also important to considers the aspect ratio of engraved cell (average cell diameter to cell depth), which also determines the filling and the release of the ink from gravure cells [18]. It can be seen in **Figure 2** that the diagonal cell opening decreases with increasing resolution resulting in lowering the ink volume available for transfer. Silver-flake conductive ink was printed at these resolutions and corresponding print quality is also shown. It can be seen that at lower resolution, the ink coverage is better than for higher resolutions, where more skipped areas can be observed. Even at the resolution of 200 lpi, the silver ink coverage is not complete. This can be further improved by engraving deeper cells or adjustment of ink viscosity to allow for better flow of ink in and out of the engraved cells. In addition, electrostatic assist is often used in traditional gravure printing to aid ink transfer by application of electric field between impression roller and gravure cylinder [5].

Gravure Printing of Fine Features for Printed Electronics

One of the basic components for electronic devices is a wire. From a design standpoint, the wire is simply a line. Various lines can function as interconnects between active blocks of integrated circuits, resistors, or as contact electrodes for individual transistors. The requirements for line dimensions differ with application. As already discussed, characteristic features of traditional gravure printing are ragged edges. With the indirect laser engraving method, however, it is possible to engrave very smooth line edges and fine lines as continuous grooves, which leads to improved line uniformity and definition. It was reported [19] that during engraving process lines have higher width then it was specified. **Figure 3** shows an example of engraved fine lines for printing of contact electrodes (source and drain) for field-effect transistor. The electrode width 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 is reduced to 85 ± 3 µm.

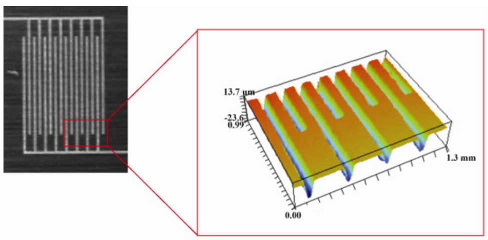

***Figure 3** Interdigitated electrodes design optical image (ImageXpert) and detailed 3D visualization (optical profilometer WYKO RST-Plus microscope)*

Line width can be further increased during printing, depending on the printing parameters and ink and substrate properties. It was also reported that line width and uniformity depends on the line orientation with respect to print direction [20]. **Figure 4** shows the line quality of gravure printed silver flake conductive ink on label paper. For cell depth of 20 µm, two resolutions were printed, 200 and 300 lpi and it can be seen that there is a significant difference in the quality of printed lines. Smoother line edges were printed in the print direction (PD) for the 300 lpi resolution, but for cross-print direction (CPD), very poor coverage and even discontinuity in printed line were observed. Significantly better coverage was achieved for 30 µm deep cells, which caused more ink to be deposited on the substrate. This, however, this also resulted in larger line width. Overall, the line width gain for the nominal 150 µm line printed with 30 µm deep cells at 300 lpi resolution was calculated to be 53 ± 7 and 96 ± 16 µm for print and cross-print direction, respectively. Furthermore, the line raggedness was reduced by around 50% with the deeper cells.

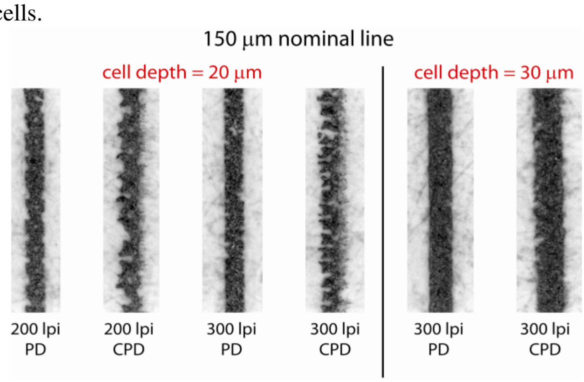

***Figure 4** Comparison of line quality for the 150 µm nominal conductive lines at different resolutions and cell depth. Lines were gravure printed with silver flake conductive ink on label paper in PD-print direction and CPD-cross-print direction.*

The quality of printed lines also depends on the materials used for printing. Ink properties, such as flow behavior, surface tension and particle size of conductive filler can influence line widening and uniformity. **Figure 5** shows the lines printed with two different silver based conductive inks on multiple label paper substrates. One of the inks contains spherical nanoparticles (20-50 nm) and the other contains silver flake particles (the average longest dimension around 1 µm). Nanoparticles based silver ink showed slightly lower average line width than line printed with flake particles in most of the cases. In addition, the standard deviation is smaller for nanoparticle silver ink (**Figure 6**) indicating higher uniformity of line edges.

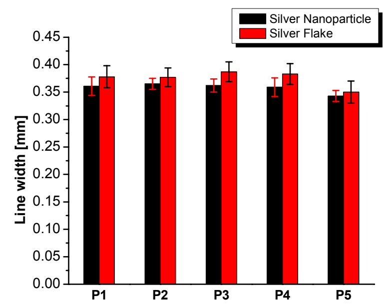

***Figure 5** Line width measured for 300 µm nominal line gravure printed with silver nanoparticle ink and silver flake ink on different label paper substrates*

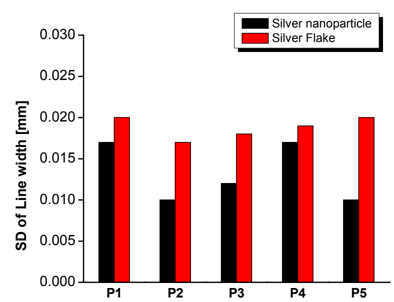

***Figure 6** Standard deviation of 300 µm line width for nanoparticles and flake inks for different label paper substrates*

When printing the source and drain electrodes of field-effect transistor (FET) for applications in printed RFID or display backplanes, it is necessary to consider both the line width and the line spacing (gap width). For better performance of FETs, it is desired that spacing between source and drain electrodes is very small. As already discussed, line widths tend to widen during both engraving and printing steps, which consequently leads to reduction of the gap width. **Figure 7** shows the linear relationship between printed and nominal line and gap dimensions for lines and gaps printed with nanosilver conductive ink on polyethylene terephthalate (PET) substrate and the quality of printed conductive lines is shown on **Figure 8**. It can be seen that narrower lines tend to print with lower coverage and some missing spots are observed. Again, this can be improved by engraving slightly deeper cells or grooves and thus deposited sufficient ink amount, which will assure the line continuity necessary for materials intended to conduct current. The smallest measurable gap was measured for 50 µm nominal gap was measured to be 22 ± 3 µm. For 30 µm nominal gap, bridging was observed due to line spreading and thus care needs to be taken when designing such fine features to avoid short circuits (**Figure 9**).

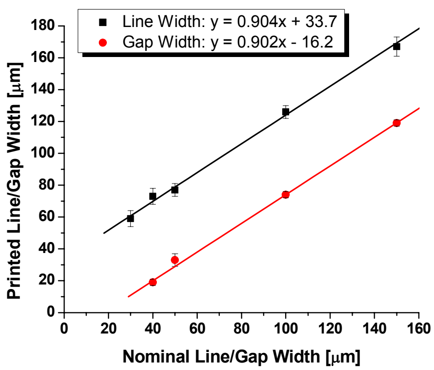

***Figure 7** Linear relationship between printed and nominal line and gap widths for nanoparticle silver conductive ink gravure printed on PET substrate*

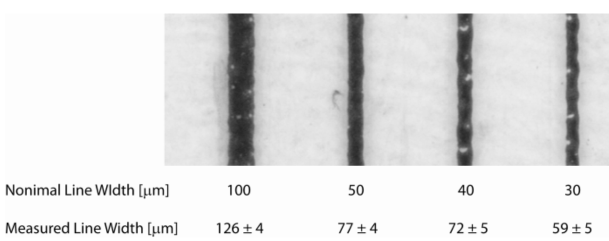

***Figure 8** The quality of fine lines gravure printing with silver nanoparticle ink on PET substrate*

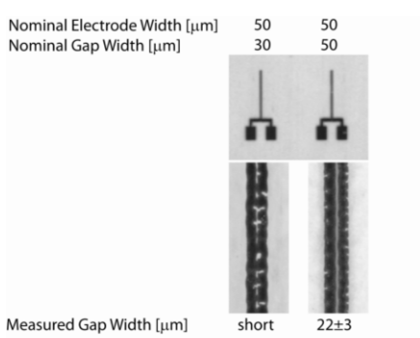

***Figure 9** The gap quality gravure printed with nanoparticle silver ink on PET substrate*

Conclusions

With printed electronics, there is an opportunity to revolutionize the electronics industry. Even though, it is not likely that printed devices will reach the performance of silicon based electronics, there is a good chance of introducing new products and applications where the high performance of silicone is not needed. Among conventional printing methods, gravure printing is probably the most suitable for printing various functional materials on flexible substrates roll-to-roll at high speeds and resolutions and it has already proven its feasibility in RFID and display applications. Gravure has been well optimized for visual printing; however, materials that are used for electronics differ from traditional graphics inks and thus often behave differently on the press. This paper shows the importance of engraving resolution and depth on the quality of printed conductive layers and traces. Higher resolution leads to improved edge definition, but with insufficient cell depth it can cause less uniform coverage. Cell dimensions need to be always adjusted based on the properties of ink, desired dry ink film thickness, as well as the substrate being printed. When printing fine lines, one must also consider directional character of gravure printing. More uniform lines are typically printed in parallel with print direction. To eliminate more ragged edge of line printed in cross-print direction, printers and engravers should be working closely together to optimize engraving for better release of ink and improved edge definition.

Author's Bio

Erika Hrehorova is currently a postdoctoral researcher at the Department of Paper Engineering, Chemical Engineering and Imaging at Western Michigan University, where she also received her PhD and MS degrees in Paper and Imaging Science and Engineering. Moreover, she received the MS degree in Polymeric Materials from the Department of Chemical Technology of Wood Pulp and Paper at Slovak University of Technology. Her main research focus is concentrated on printing of functional inks for printed electronics applications by using various printing methods.

References

[1] D. R. Gamota, , P. Brazis, K. Kalyanasundaram, J. Zhang (Ed.), "Printed Organic and Molecular Electroncis," Kluwer Academic Publishers, Norwell, Massachusetts, 2004, pp. 695

[2] E. Zeira, 'Rheology considerations in printed electronics' IDTechEx Printed Electronics USA 2007, San Francisco, CA, November 12-15, 2007

[3] J. E. Atkinson, et al., Western Michigan University – unpublished results (2008)

[4] R. H. Leach, , et al. (Ed.), The Printing Ink Manual, 4th Edition, Van Nostrand Reinhold London (1988), pp. 872

[5] K. Gillett, et al, Gravure – Process and Technology, GAA and GEF, Rochester, 2nd Edition, New York (2003)

[6] M. F. Bohan, T.C. Claypole, D.T. Gethin, "The Effect of Process Parameters on Product Quality of Rotogravure Printing," Proc. of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture, 214, 3 (2000) p. 205 - 219

[7] M. Rebros, E. Hrehorova, B. J. Bazuin, M. K. Joyce, P. D. Fleming, A. Pekarovicova, "Rotogravure Printed UHF RFID Antennae Directly on Packaging Materials," TAGA 60th Annual Technical Conference, San Francisco, CA, 16-19 March, 2008

[8] M. Tuomikoski,et al. " Manufacturing of polymer light-emitting device structures, Proceedings of SPIE - The International Society for Optical Engineering 6192, art. no. 619204 (2006)
[9] J. Puetz, M. A. Aegerter, "Direct gravure printing of indium tin oxide nanoparticles patterns on polymer foils," Thin Solid Films 516 (2008) 4495–4501
[10] E. Hrehorova, M. Rebros, A. Pekarovicova, P. D. Fleming, V. N. Bliznyuk, "Characterization of Conductive Polymer Inks based on PEDOT: PSS, TAGA Journal, vol. 4, p. 219-231 (2008)
[11] S. Rogojevic, et al. "Method for Controling Quality in Gravure-Printed Layer of an ELectroactive Device," US Patent Application Publication No. US2006/0207457 A1, September 21, 2006
[12] C. Kim, et al., "Printable Cross-Linked Polymer Blend Dielectrics. Design Strategies, Synthesis, Microstructures, and Electrical Properties, with Organic Field-Effect Transistors as Testbeds," J. *Am. Chem. Soc.,* 130 (21), p.6867–6878 (2008)
[13] W. Siegenthaler, "Lasers in Engraving," Gravure Cylinder User Group, Nashville, TN, March 30 – April 1, 2004
[14] G. Hennig, K.H. Selbmann, S. Brüning, "Laser Processing in Printform Fabrication," Conference on Lasers and Electro-Optics CLEO 2007, 6-11 May 2007
[15] G. Henning, K.H. Selbmann, A. Brocklet, "Laser Engraving in Gravure Industry," Proc. of SPIE: Workshop on Laser Applications in Europe, 6157, 61570C (2006)
[16] Annonymous "Laser Precision for Gravure and Flexo," http://www.daetwyler.com/user_content/editor/files/Fact_sheets_digilas_en/4p_dig_eng_eu.pdf; Accessed on 6/26/2008.
[17] L. W. Schwartz, P. Moussalli, P. Campbell, R. R. Eley, "Numerical modelling of liquid withdrawal from gravure cavities in coating operations," *Transactions of the Institution of Chemical Engineers*, 76(A) p. 22–28 (1998)
[18] N. Kapur, "A parametric study of direct gravure coating," *Chemical Engineering Science* 58 (2003) 2875 – 2882
[19] E. Hrehorova, "Materials and Processes for Printed Electronics: Evaluation of Gravure Printing in Electronics Manufacture" PhD Dissertation, Western Michigan University, June 2007, pp. 142
[20] E. Hrehorova, A. Pekarovicova, P. D. Fleming, "Evaluation of Gravure Printing for Printed Electronics," TAGA 60th Annual Technical Conference, San Francisco, CA, 16-19 March, 2008