Gravure Printing of Conductive Inks on Glass Substrates for Applications in Printed Electronics

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ABSTRACT

In graphics, gravure printing is the preferred method for printing high quality, fine dimension graphics using high-speed roll-to-roll or sheet fed presses. Gravure printing typically employs flexible and compressible substrates such as various papers and polymer films. In electronics, glass substrates are a common, if not preferred, substrate in many applications, particularly displays and photovoltaics. In combining printing with glass substrates, challenges exist in adapting contact-based printing methods such as gravure to the mechanical properties of the more rigid substrates. In this work, sheet-fed gravure printing has been successfully used to print silver-based conductive inks on glass substrates. Various features were designed and printed to evaluate conductive layers in terms of their printability and electrical performance. The independent variables include gravure cell dimensions, trace orientation with respect to printing direction and ink type. Results from this work provide an insight into the science of gravure printing on glass by correlating the independent variables to printed feature quality and electrical performance.

EXPERIMENTAL

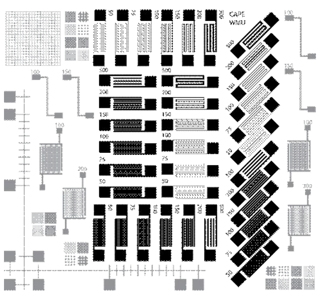

Fig. 1 Section of printing design (meander lines and lines with different spacing (gaps) at 0, 45, 90° to print).

Printing design (Fig. 1) - set of meander line resistors that were used for both printability evaluation and DC resistance testing. Test structure line (trace) widths were designed to range from 50 µm to 500 µm. In order to evaluate directionality effects of gravure printing, traces were designed at three different angles with respect to the print direction (0, 45 and 90°). For the evaluation of printed gaps, a group of 500 µm wide lines with different spacing was included.

Gravure cylinder preparation - indirect laser method - laser ablation of a protective mask on a copper surface, followed by a chemical etching of the copper layer. After etching, the cylinder is chromium plated and finished using traditional methods.

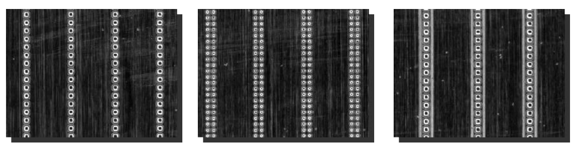

Fig. 2 Engraving for traces with different nominal width. (Images taken with ImageXpert Image Analysis System at 40x magnification)

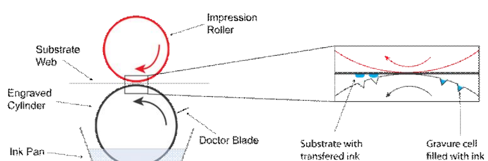

Fig. 3 Basic principle and arrangement of the components for gravure printing.

Printing trial - sheet-fed gravure proofer, Prüfbau Rotogravure Printability Tester (by Prüfbau, Germany); printing speed of 250 fpm (1.27 m/s).

Two silver-based conductive inks - silver flakes and silver nanoparticles as the conductive filler (solids content of silver flake and silver nanoparticle inks - 80 wt.% and 40 wt.%).

Printed inks were initially cured using a heat-gun for 1 minute followed by post-curing treatment in a convection oven at 120 °C for 10 min.

Substrate - Glass substrates were supplied by Corning Incorporated (Corning, NY). Dimensions of were 110 mm x 310 mm and 0.7 mm thick. A UV curable acrylate coating (<10µm thick) was applied to the substrate surface to ensure ink adhesion (Ra roughness ≈ 1 nm, Surface energy ≈ 50 mN/m).

CONCLUSIONS

- The nanosilver ink tends to spread more resulting in wider lines than silver flake ink (Fig. 4). Lines printed with nanosilver ink also showed much lower ink film thicknesses than those printed with silver flake ink (Fig. 11).
- There was more ink transferred for 100 µm (single row of gravure cells) than for 150 µm (two rows of smaller cells) nominal lines (Fig. 2). This was supported by line width, line thickness, and resistance measurements.
- If moat surrounding the pattern to be printed is connected to the main gravure cells (Fig. 7), improved printability can be achieved as opposed to when the moat is separated from the main cells.
- The highest line spreading was found for 90° then for 45° lines, and the narrowest lines were printed at 0° to the print direction (Fig. 5).
- Among printed and measurable gaps, the narrowest gaps printed with nanosilver ink on glass were measured as 36 ± 8 µm.
- Silver flake ink consistently provided lower DC resistance values than nanosilver ink (Fig. 8).
- When considering the thickness of printed lines, nanosilver ink has better applicability since it printed more than 4 times thinner and smoother ink film than silver flake ink (Fig. 10).

RESULTS

Sample evaluation:

Quality of printed lines and gaps - ImageXpert Image Analysis System.

Ink film thickness - vertical scanning interferometry (VSI) using a WYKO RST-Plus microscope.

Electrical DC resistance - 2 point probe local measurement with standard ohm-meter settings on the Keithley 2602.

Line and Gap Quality

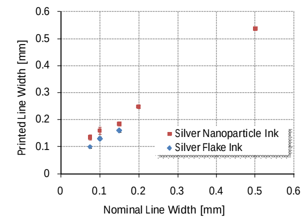

Fig. 4 Comparison of printed vs. nominal line width in print direction for two conductive inks printed on glass substrate.

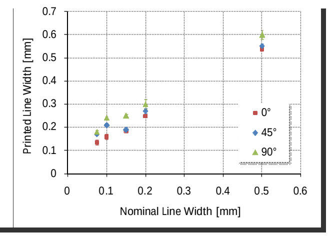

Fig. 5 Printed vs. nominal line width for nanosilver ink printed on glass at three different angles to print direction.

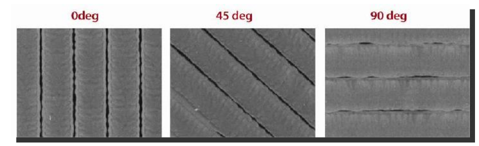

Fig. 6 Comparison of gap quality of 50 µm nominal gap for nanosilver ink printed at three different angles to print direction.

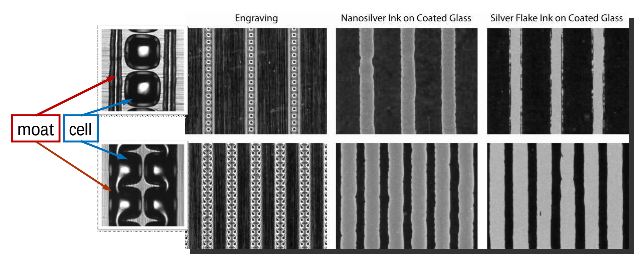

Fig. 7 Comparison of printability of 200 µm nominal line by using two different engraving approaches.

Ink Film Thickness

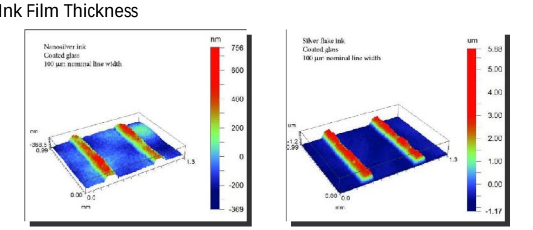

Fig. 10 The 3D images of 100 µm nominal line printed with nanosilver ink (left) and silver flake ink (right) on glass substrate (measured by a vertical scanning interferometry (VSI) using a WYKO RST-Plus microscope).

Electrical Properties

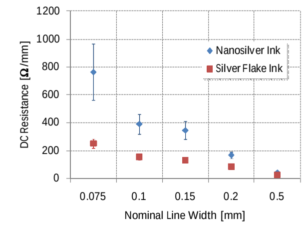

Fig. 8 DC resistance values for resistors with different nominal line widths for two conductive inks printed (lines printed in parallel to print direction, 0°).

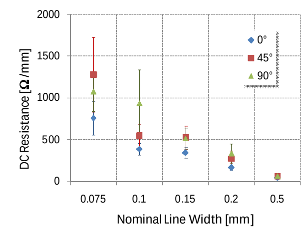

Fig. 9 DC resistance values for resistors with different nominal line widths for nanosilver ink printed at three different angles to print direction.

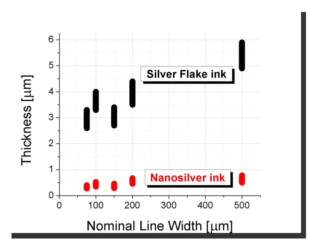

Fig. 11 Comparison of line thickness range for different nominal line widths for the two conductive inks.