Electrical Performance Analysis of Gravure Printed Conductors on Film Substrate using Line Screen, Line Width and Sintering Method Factors

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Keywords: heat, thermal, conductive, gravure

Abstract

Thermal heating requires long sintering times, ranging from tens of minutes to hours, at high temperature levels. Most film substrates cannot be processed in a high temperature environment as heat can deform their physical structure. Photonic sintering, as an alternative method, can sinter conductive ink layers on substrates in microseconds without deforming the physical structure. In this study, conductive traces printed with nano silver based gravure ink on PET film by using a RT K-gravure printing proofer. Printed ink layer then sintered both thermally and photonically. Electrical performance analyzed in response to sintering method, line width and line screen using factorial design statistical analysis. The analysis proved that the difference in electrical performance provided by thermal and photonic sintering is insignificant and practically same. The sheet resistance values at 100 lpi line screen was 0.48 Ω/sq. for photonic, 0.40 Ω/sq. for thermal sintering; 0.84 Ω/sq. for photonic, 0.99 Ω/sq. for thermal sintering at 200 lpi.

1. Introduction

One of the emerging technology in graphic arts field is printed electronics. Gravure is the leading printing method for the manufacturing of low cost flexible electronics, for instance RFID tags, sensors and smart packaging that can monitor information about products' location, freshness or shelf life, respectively [1-4]. Gravure printing has been studied heavily for printed electronics, due to its ability to print smooth and uniform ink layer at high resolution as well as printing thicker ink films than other printing processes are able to, which is very useful to print electronics [1, 5-9].

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Parameters such as line screen, dot gain play an important role in the quality of graphic images. For instance, line screen is the number of lines per square inch (lpi) on a plate in gravure printing [10], and a 120 lpi line screen provides more details in comparison to 60 lpi. The higher the line

screen, the better the image quality. But there is little if any research presenting how these parameters affect electrical functionality. Printed electrical components, such as electrodes, capacitors and resistors among others, require special inks with electrical properties (*i.e. conductivity, semi-conductivity, dielectric*), called functional inks, to create desired layers of a final product. Schematics of an electroluminescent device, and functional ink layers can be seen in Figure 1.

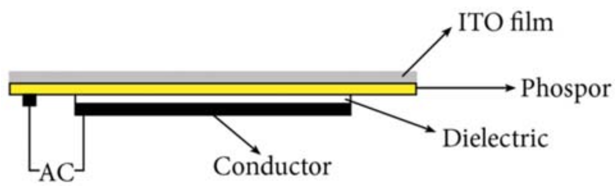

Figure 1. *Typical construction of electroluminescent device*

Most functional inks require sintering (*suchlike drying*) after printing to improve or bring out the functionality. Pigments in an ink composition are covered with ligand to keep them separate for good dispersion stability and ink transfer. Sintering process, (*schematically presented in Figure 2*) helps eliminating ligand and connecting functional particles to form a continuous layer, so conducting occurs. To make the electrical component as functional as possible, it is important to know how printing parameters and sintering methods govern the functionality.

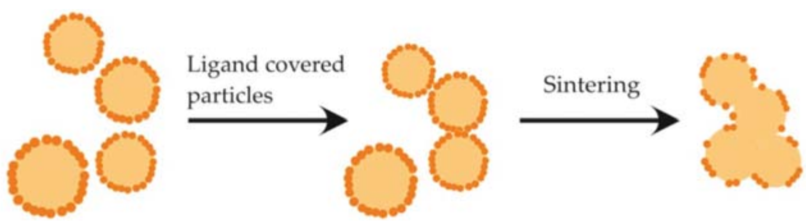

Figure 2. *Schematics of sintering process*

Although there are various sintering methods available, this study focuses on thermal and photonic sintering methods. Conventional thermal heating in an oven is the oldest sintering method. It requires long processing times, ranging from minutes to hours, at high temperatures [11]. Film substrates such as PET, PEN, PI and PC (*polyethylene terephthalate, polyethylene naphthalate, polyimide and polycarbonate*) may not be processed in a high temperature environment long time as heat can deform their physical structure. Photonic sintering on the other hand, can sinter in microseconds, without deforming the substrate [12]. In general, conventional thermal heating requires tens of minutes processing time at 100-220°C (212-428°F) temperature. While photonic sintering uses various intense radiant energy to heat conductive inks in microseconds. After sintering, the printed conductive ink layers are generally quantified by measuring sheet resistance value with a four-point probe sourcemeter.

A full factorial design analysis provides a p-value to determine the significance of the test results.

Based on the p-value and significance level ($\alpha = 0.05$), a strong evidence for factors and theinteraction between them can be presented. Theoretically, if p-value is less than 0.05, then null hypothesis (H_0) is rejected, meaning the difference in sheet resistivity significantly differ from the other. If p-value is greater than 0.05, then rejecting null hypothesis fails, meaning the difference in sheet resistivity is not significantly different from the other.

In this study, statistical model used to investigate if there is a significant difference between the thermal and photonic sintering methods, including line screen and line width (*gain*) parameters. The hypothesis proposes that if the difference is insignificant, photonic sintering would be a roadmap to increase range of substrate as well as to decrease costs that can raised due to extended period of conventional sintering times at high temperatures.

2. Materials and Methodology

Nano silver conductive ink TEC-PR-20 (*Inktec*) was printed on heat stabilized Teijin Melinex ST506 PET substrates (*Dupont*) by using a gravure K-printing proofer (*RK Print Coat Instruments*) with an engraved plate that has four different line screen design (*Figure 3*).

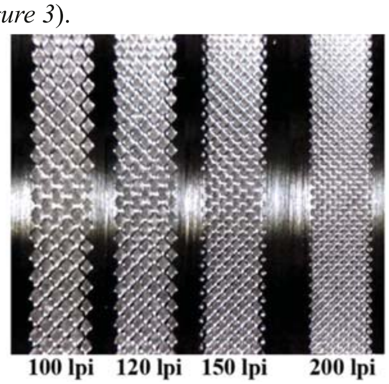

Figure 3. *Different line screens on gravure plate*

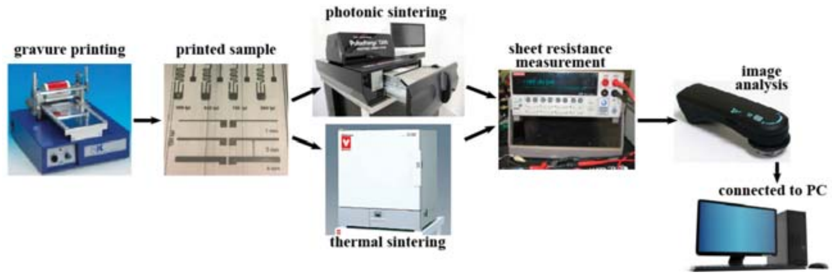

Figure 4. *Experiment setup*

The PET was selected as heat stabilized to prevent physical destruction during the experiment, so sintering capabilities of the two system could be assessed objectively. A DX300 model convection oven (*Yamato*) was employed at 110°C for 20 minutes for conventional sintering. PulseForge 1200 model (*NovaCentrix*) used in once through mode, 20 fpm web speed, 2.0 overlap factor, 300 V voltage and 1000 microseconds (*=0.001 seconds*) pulse length was applied for photonic sintering. Sheet resistivity was measured with a 4-point-probe sourcemeter (*Keithley*). The Haldor Topsøe geometrical factor was used to correct the sheet resistivity value based on the printed line width and length [13, 14]. The line widths were then measured with an UM-02 digital microscope (*Ihara*) to assess the line gain. The number of replicates for the experiment was three. Figure 4 represents the experiment setup.

The hypotheses for the study are whether any of the differences between the means of sheet resistance from the two sintering method is statistically significant (meaning sintering methods has a significant effect on sheet resistance).

$$H_0: \mu photonic = \mu conventional$$

$$H_a: \mu photonic \neq \mu conventional$$

If the average resistivity gathered from photonic sintering is equal to the average value of conventional sintering, then photonic sintering would easily be selected over conventional sintering in practice. Significance level was set to $\alpha = 0.05$ (95%). The data analyzed with a general full factorial design using Minitab 17. The design of experiment is presented in Table 1.

Factors	Levels	Values	Replicates
Sintering methods	2	Photonic, Conventional	3
Line screen (lpi)	4	100, 120, 150, 200	3
Line width (mm)	3	1, 2, 4	3

Table 1. *Factor information – sintering method and line screen effect on sheet resistivity*

3. Results and Discussion

In graphic printing, image quality is generally controlled by screen ruling (the number of dots per inch on a plate). The higher the dot amount, the better the image quality. Similar to this, one may expect to get better electrical performance from the conductive ink printed with the higher line screen. For this study, the electrical performance was quantified by sheet resistance and the lowest resistance values are preferable. Figure 5(a) represents that the lowest value was gathered both for conventional and photonic sintering at around 100 and 120 lpi. Unlike graphic printing, the preferable results were achieved using smaller line screen. The reason for this is that if line screen decrease in gravure printing, the depth and width of the cell opening increases. Increased cell opening provides more ink volume, therefore the amount of pigment particles that are transferred on a substrate increases as well. More pigment particles form more connection, thus least sheet resistance (more conductivity).

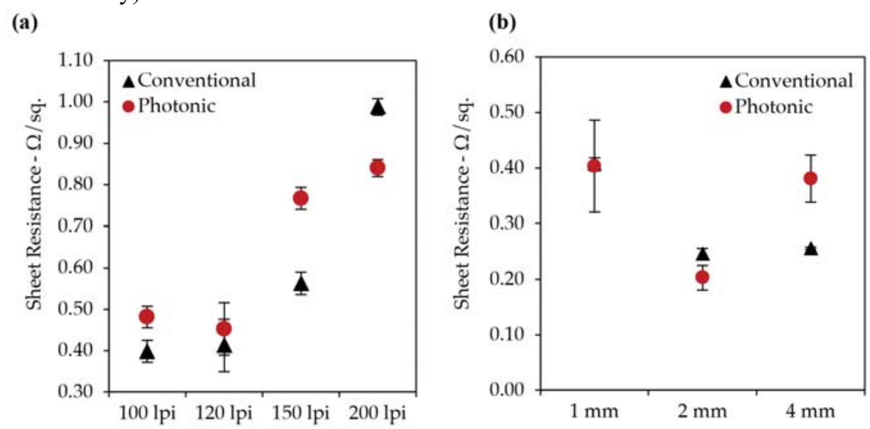

***Figure 5 (a).** sheet resistance in response to line screen;*
***(b).** sheet resistance in response to line screen at 120 lpi*

Since the significance level was set to $\alpha = 0.05$, for any value of $p \leq \alpha$ will fail to reject H_0 and for any value of $\alpha \leq p$ will reject H_0. The p-value of 0.173 in Table 2 for sintering indicates that the average resistance values are equal and the effect of sintering method on electrical performance is not significant.

Factors	**p-value**
Sintering	0.173
Line screen (lpi)	0.000
Sintering*line screen	0.010

***Table 2.** Sintering method and line screen effect on sheet resistance*

On the other hand, the effect of line screen and its interaction with the sintering method is significant. By changing the line screen, the sheet resistance value can be optimized. The average sheet resistance results listed in Table 3 shows that 200 lpi line screen provides the highest sheet resistance value, which is less favorable.

Line Screen	Sintering method	Mean	St. Dev.
100 lpi	Photonic	0.4833	0.0306
	Conventional	0.4000	0.0656
120 lpi	Photonic	0.4533	0.0635
	Conventional	0.4100	0.0608
150 lpi	Photonic	0.7700	0.0265
	Conventional	0.5633	0.0208
200 lpi	Photonic	0.8400	0.0173
	Conventional	0.9900	0.187

Table 3. *Average sheet resistance results in response to line screen and sintering method*

In Table 4, the sheet resistance values in response to line width and sintering method is presented. Similar to line screen result, the effect of sintering method also statistically is not significant on the sheet resistance in response to line width since the p-value of 0.861 is bigger than the $\alpha = 0.05$.

Factors	**p-value**
Sintering methods	0.861
Line width	0.000
Sintering*Line width	0.201

Table 4. *Sintering method and line width effect on sheet resistance*

The results in Figure 5(b) and Table 5 shows the average resistance values at different line widths. The exception was the photonic curing for the 4-mm line where more photons may probably be needed to fully cure the ink layer than were received during the residence time in the sintering unit. Both line screen and line width results show that photonic sintering provides almost the same sheet resistivity values in 1000 microseconds (=0.001 seconds), while the conventional takes 20 minutes.

Line Width	**Sintering method**	**Mean**	**St. Dev.**	**Minimum**	**Maximum**
1 mm	Photonic	0.4068	0.0827	1.23	1.30
	Conventional	0.4033	0.0120	1.23	1.30
2 mm	Photonic	0.2029	0.0223	2.21	2.37
	Conventional	0.2460	0.0098	2.18	2.31
4 mm	Photonic	0.3807	0.0424	4.07	4.12
	Conventional	0.2563	0.0017	4.22	4.31

Table 5. *Average sheet resistance results in response to line width and sintering method*

Line Screen	Sintering method	Mean	St. Dev.
1mm	Photonic	1.26	0.04
	Conventional	1.25	0.04
2mm	Photonic	2.27	0.09
	Conventional	2.23	0.07
4mm	Photonic	4.10	0.03
	Conventional	4.26	0.04

Table 6. *Average line gain results in response to line width and sintering method*

Table 6 and Figure 6 represents the comparison of the gain in printed lines gathered with 120 lpi line screen. Both conventional and photonic samples had similar amounts of gain, mainly due to the nip pressure between the gravure plate and impression cylinder, not because of the sintering method. It was observed that as the line width gets thinner, the gain gets more.

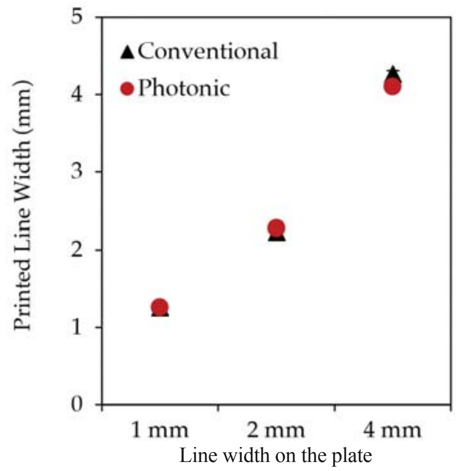

Figure 6. *Printed line width in comparison to its width on the plate*

4. Conclusion

This study presented using a factorial design analysis that photonic sintering provides practically same sheet resistance value in a millisecond, while conventional thermal oven in 20 minutes. The nano silver conductive ink printed with lower line screen values on the heat stabilized PET shown to have less sheet resistance. It was found that like dot gain in graphic printing, conductive line width also gain size during printing. This is critically important and must be considered to incorporated into physics based electrical sensor simulation solutions. It was found that the common conventional sintering methods require long processing time at high temperatures, and are not adaptable to the nature of roll-to-roll high speed gravure printing. Conventional sintering limits not only manufacturing time and cost, but also minimize substrate choice and feasibility of in-line sintering. Photonic sintering provides many variables as mode, web speed, overlap factor, voltage and time, which can be used in design of experiment studies to optimize the response value (*such as sheet resistance, conductivity, resistivity*).

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Appendix

1. General factorial regression: 4-probe sheet resistance versus sintering, line screen

Analysis of Variance

Source	***DF***	***Adj SS***	***Adj MS***	***F-Value***	***P-Value***
Model	7	1.04896	0.149852	24.22	0.000
Linear	4	0.95052	0.237629	38.40	0.000
Sintering	1	0.01260	0.012604	2.04	0.173
Line screen	3	0.93791	0.312637	50.53	0.000
2-Way Interactions	3	0.09845	0.032815	5.30	0.010
Sintering*Line screen	3	0.09845	0.032815	5.30	0.010
Error	16	0.09900	0.006187		
Total	23	1.14796			

Model Summary

S	***R-sq***	***R-sq(adj)***	***R-sq(pred)***
0.0786607	91.38%	87.60%	80.60%

2. General factorial regression: 4-probe sheet resistance versus sintering, line width

Analysis of Variance

Source	***DF***	***Adj SS***	***Adj MS***	***F-Value***	***P-Value***
Model	5	0.264761	0.052952	33.92	0.000
Linear	3	0.259028	0.086343	55.31	0.000
Line width	2	0.258978	0.129489	82.95	0.000
Sintering	1	0.000050	0.000050	0.03	0.861
2-Way Interactions	2	0.005733	0.002867	1.84	0.201
Line width*Sintering	2	0.005733	0.002867	1.84	0.201
Error	12	0.018733	0.001561		
Total	17	0.283494			

Model Summary

S	***R-sq***	***R-sq(adj)***	***R-sq(pred)***
0.0395109	93.39%	90.64%	85.13%