AN INTRODUCTION TO THE PROCESS OF PRINTED ELECTRONICS

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ABSTRACT
Printed electronics (PE) is impacting almost every branch of manufacturing. The printing of electronics on mechanically flexible substrates such as plastic, paper and textile, using traditional printing techniques, provides novel applications for wearable and stretchable electronics. Government sponsored consortiums, universities, contract printers, startups and global manufacturers are developing processes to bring this technology to market faster, more cost-effectively and at scale. By increasing the speed of technology adoption while following industrialization best practices, industry researchers aim to create processes that ramp up the scale of production for simple circuits and integrated conductive structures.

Key words: Flexible Electronics, Printed Electronics, Process Development, Screen Printing

INTRODUCTION
Printed electronics (PE) is an emerging technology that uses various printing techniques for manufacturing electronics. PE has gained considerable interest for fabricating low-cost and large-area flexible electronic devices using traditional printing processes [1]. It is predicted that in the next two decades, the field of printed electronics will capture a significant portion of the market due to the advantages of printing. A forecast from IDTechEx reports that the printed electronics market will exceed $300 Billion in the next 20 years [2]. PE offers numerous advantages such as high throughput, reduced usage of resources, lower manufacturing temperature and much less complex fabrication processes than conventional silicon-based technology which involves high-vacuum, high-temperature deposition processes and sophisticated photolithographic patterning techniques [3].

PE has been used for the manufacture of radio frequency identification tags (RFID's) [4-5], displays [6-7], organic thin film transistors [8-9] and sensors [10], using inkjet, gravure, flexographic and screen printing techniques. The manufacturing of PCBs on flexible substrates such as plastic, paper and textiles using traditional printing techniques offer promising opportunities for PE [11-13]. However, there are only few studies academically reported on the adaption of traditional printing methods on flexible substrates for the development of electronics.

TYPES OF PRINTING TECHNIQUES USED IN PE
PE utilizes high throughput printing techniques, such as roll-to-roll gravure, flexography, inkjet and screen printing of chemical solution processed electrically functional materials (conductive, resistive, semi-conductive and dielectric inks) for layer on layer fabrication of electronic sensors, devices and circuits.

Gravure printing
Gravure printing is known for its high print quality, high print speeds, variable film thickness, use of low viscosity inks and simplicity of transferring the ink onto the substrate. The gravure cylinder (image carrier), doctor blade, impression roller and ink fountain are the main components of the typical gravure printing process as shown in Figure 1. The impression roller is made of rubber. Steel is the material used for the doctor blade. Chromium and copper coated steel are used in the manufacture of the gravure cylinder. The image carrier is etched electromechanically, chemically or by laser to form an image area, which is usually made up of small gravure cells. The gravure printing transfers large amounts of ink to the print area at high speeds with nominal distortion. As the cylinder rotates, it picks up ink into the small cells and transfers it to the substrate with the impression cylinder. Then the doctor blade wipes the excess ink remaining off the cylinder. The angle of the doctor blade also plays a key role in print process. Transferring the ink from the cells onto the substrate is assisted by the impression roller [14].

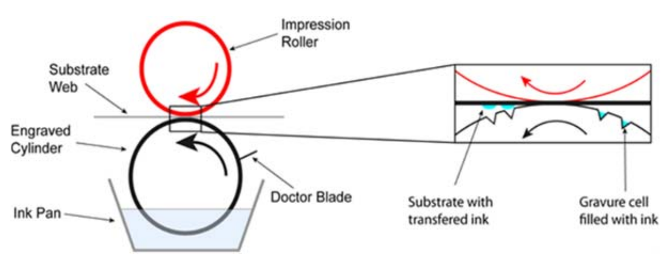

Figure 1. Schematic Gravure printer

Flexographic printing
Flexographic printing is known for depositing a wide range of thicknesses with the same resolution. In the flexographic printing technique, an indirect printing process uses the same nominal resolution plate with anilox rolls of different cell volumes. Impression cylinder, plate cylinder, anilox roller, doctor blade and inking unit are the main parts of the flexographic printing are shown in Figure 2. The material

used for the doctor blade and anilox roller is usually stainless steel. The flexo plate is made of either a photopolymer or rubber. The image areas of the plate are raised with respect to the surface of the plate. The anilox roller transfers the ink from the ink pan to the image areas of the plate cylinder. Transferring the ink from the image areas onto the substrate is assisted by the impression cylinder [14].

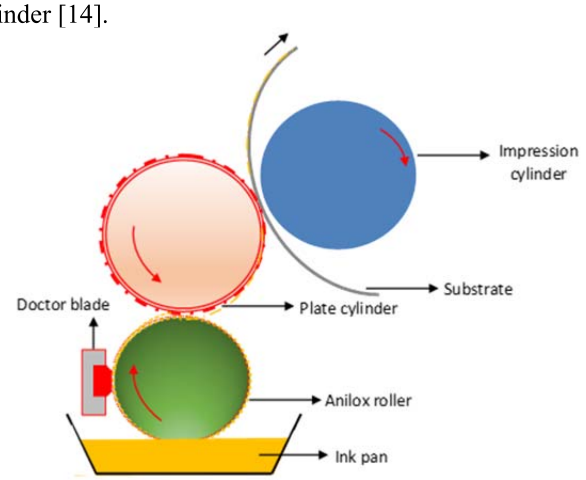

Figure 2. Schematic of Flexographic printing

Inkjet printing

The main advantage of an inkjet printing process is the no need for a physical mask or image carrier. Instead, inkjet printing uses a direct deposition technique and a virtual digital image carrier. Inkjet printing is known for thin ink deposits and is classified into either continuous inkjet or drop-on-demand inkjet based on the ink transfer method used. Drop-on-demand inkjet is further categorized as thermal inkjet and piezo inkjet printing processes. Figure 3a shows continuous inkjet printing where a continuous stream of ink is generated. The ink is deflected towards the substrate by use of a voltage source and the non-deflected ink is fed back into the cartridge. Drop-on-demand inkjet deposits ink with respect to image signals using either thermal (Figure 3 (b)) or piezo electric (Figure 3 (c)) ink droplet generation techniques [14].

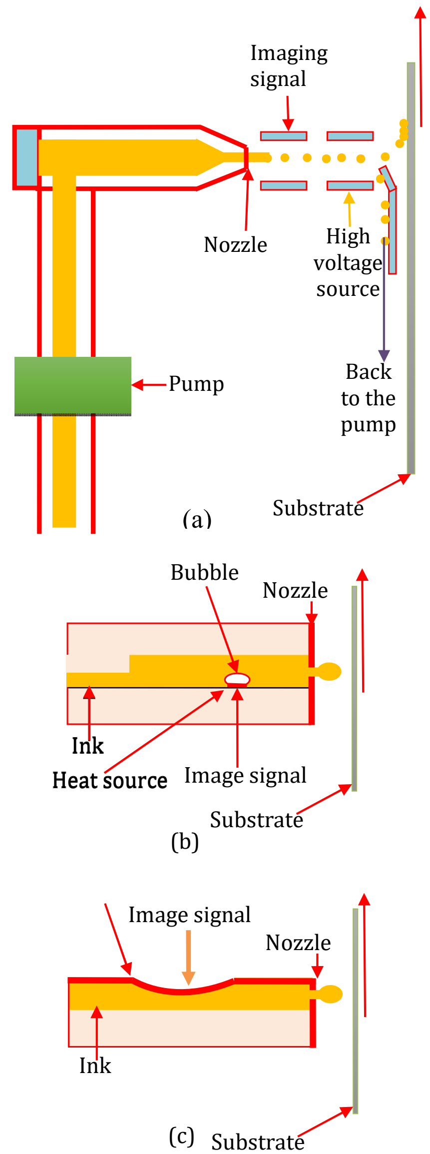

Figure 3. (a) Continuous, (b) thermal and (c) piezo electric drop on demand inkjet.

Screen printing

Screen printing uses a porous mesh image carrier (screen), which yields thicker ink deposits compared to other printing methods. The typical screen printing process is shown in Figure 4 (a). A squeegee and screen printing plate are the main components of the screen printing process. A screen printing plate (Figure 4 (b)) consists of screen fabric, stencil and frame. The materials used for the screen fabric and stencil vary depending upon the use of solvents and cleaning agents. Polyurethane is the usual material used for the squeegee. Ink is applied on top of the screen. The squeegee is used to sweep the ink on top of the screen with pressure. The ink passes through the screen and transferred onto the substrate which is typically has the form of a single sheet [14].

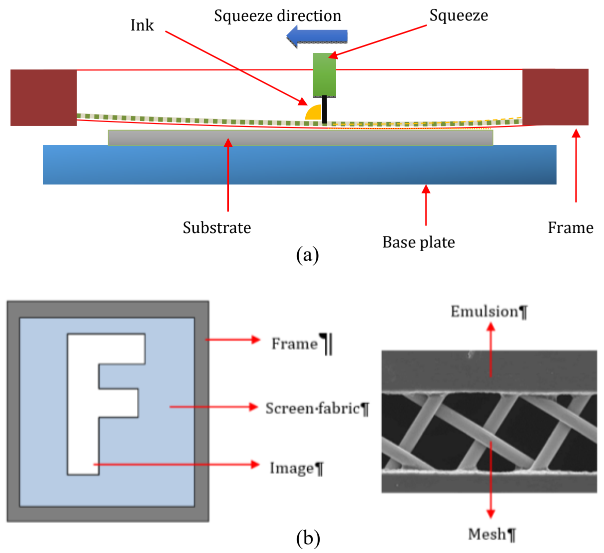

Figure 4. (a) Screen printing process and (b) screen printing plate

The electronic manufacturing industry has optimized sheet based stencil printing over several decades. Comparison of screen printing and solder paste stencil print process in terms of materials, substrates and process is shown in Table 1.

Table 1.

	SMT	Screen printing
Materials	Solder paste	Conductive inks
	Solder powder	Metal flakes
	Particle size: 20 – 38 µm (Type 4 powder)	~ 5 - 30 µm
Substrates	PCB's	Thin flexible films/glass/fabric
Stencil / Screens	Apertures opening	Emulsion open area
	Stencil thickness	Emulsion thickness
	Foil (stainless steel (SS))	Mesh (SS & polyester)
Printing	Single print	Flood / Print
	On contact printing	Print gap
Squeegees	Stainless steel	Polyurethane
Flood bar	N/A	Stainless steel
Industry standards	Established IPC standards	IPC standards under development

Comparison of printing techniques

A comparison of the most common printing techniques is shown in Table 2 [15].

Table 2.

	Gravure	Inkjet	Flexography	Screen
Resolution (µm)	15	15	20	30
Printing speed (m/min)	8-100	0.02-5	5-180	0.6-100
Ink film thickness (µm)	0.02- 12	0.01-0.5	0.17-8	3-30
Image carrier	Gravure cylinder	Virtual carrier	Flexo plate	Stencil

DEVELOPMENT OF PRINTED ELECTRONICS

Even though PE promises great advantages, there is a fair amount of effort required during its development. Selecting suitable inks print processes must be designed to maintain overall compatibility of the printed layers' materials to ensure reliable printed electronic structures.

The relation between the surface energy of the substrate and surface tension of the ink is critical. As a rule-of -thumb, the surface energy of the substrate should be at least 10 dynes/cm greater than the surface tension of the ink. The contact angle of the ink on the substrate should be less than 90° to permit adequate wetting. Uneven evaporation of the solvent resulting in coffee ring effect is also an important factor to be considered. This can be best addressed by mixing solvents of different boiling points and surface tensions in ink formulations

The choice of a suitable substrate is usually driven by cost, ink drying/curing parameters and end-user requirements. Some of the important properties of substrates include but are not limited to: thermal & mechanical stability, flexibility, solvent resistance, surface roughness, surface energy, recyclability and resistance to moisture, gas & vapor transition (barrier properties). Polymer, paper and glass are the typical substrates used in PE. Polyethylene terephthalate (PET), polymide (PI) and polycarbonate (PC) are some of the most commonly used polymer substrates in PE. Each of these polymer substrates has its own advantages and disadvantages. Choice of these substrates is driven by end user requirements and applications. For instance, PET and Polyethylene naphthalate (PEN) are widely used for low cost flexible circuit applications. PI is chosen for high temperature requirements (~300 °C). PC is used for in-mold electronics. Out of all the polymer substrates, PET is the most commonly used in PE industry. Polyethylene is connected by the terephthalate group in PET which is more resistant to humidity and higher tensile strength compared to paper and also cheaper compared to PI and PC. Usually PET is thermally stabilized before production to reduce the shrinkage on press.

Another important factor to consider in the PE is complexity of the inks. Viscosity is one of the major factors considered in the print process. For instance, screen printing needs very high viscous inks (paste inks) on the other hand, inkjet print technology needs very low viscous inks (water based inks). Leading conductive inks are formulated using conductive flake particles, resins and solvent. Some ink formulations include additives improving ink deposition and end use properties however, this can affect the electrical properties of functional inks and thus influence the overall functional performance of the printed samples. Parameters used on the printing press have significant impact on the print quality. Publicly available process guidelines, relationship between printing process parameters and their influence on printed layer morphology and resulting electrical behavior are limited at this point given the emerging nature of the technology and know-how being kept captive.

EXPERIMENTAL WORK

In this work, the authors have included Jabil's internally available sheet printing capacity to study the effect of process variables in printing of conductive silver inks. Design of Experiments (DOE) were performed to identify the effects of printer and screen parameters on ink deposition and the post dry sheet resistance of conductive silver ink traces. A conventional SMT based screen printing equipment set has been used to print the silver inks on flexible polyester substrates. Silver inks and polyester substrates used in this study were commercially available from different vendors. A test vehicle for screen printing has been designed to study the effect of printing in direction parallel, perpendicular and diagonal to the squeegee stroke. Dimensions of the straight and meander lines are normalized to a given number of squares, i.e., ratio to the length and width of all the lines were maintained constant value. In this study, line widths were chosen from A to G where G being the higher width and length compared to A. Figure 5 shows the image of the designed test vehicle.

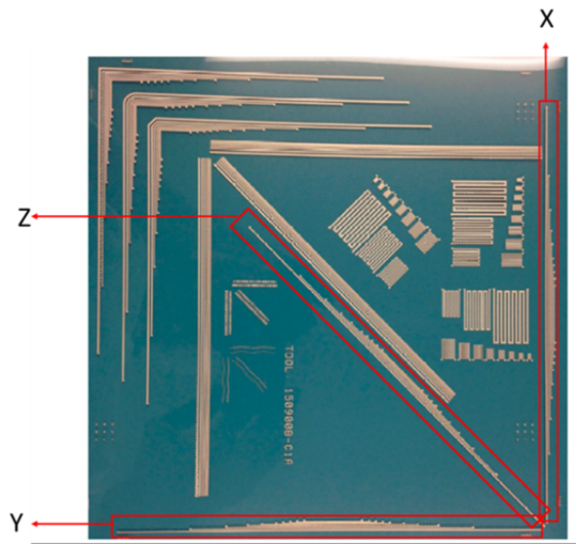

Figure 5. Test vehicle designed for screen printing the conductive inks

The screens containing the test vehicle image were fabricated and assembled by commercial vendors using the predefined screen parameters. Stainless steel was used as material for mesh. Mesh angle and type of emulsion were kept constant for all screens fabricated. Screen parameter specifics were chosen considering input recommendations from the ink suppliers. Table 3 summarizes the process variables used in this study.

Table 3.

Variables	Lower limit	Upper limit
Print speed	Print speed A	Print speed B
Print pressure	Print pressure A	Print pressure B
Print gap	Print gap A	Print gap B
Mesh	Mesh A	Mesh B
Emulsion thickness	A Emulsion thickness	B Emulsion thickness
Line width	Line width A	Line width G

Different print variables in this DOE were chosen in order to explore the limits and effects of SMT screen printer settings and interaction on printed electronics processing. As shown in Table 3, print parameters such as print speed, print pressure and print gap were selected as some of the variables in DOE. Variable B is always greater than variable A, i.e., print speed B is greater than the print speed A. Effect of screen parameters (mesh and emulsion thickness) is also included as variables for executing the DOE's. In this case, mesh B is finer than the mesh A and emulsion thickness B is greater than emulsion thickness A. Absolute values were different for different set of materials and could not be published or disclosed due to the company's confidentiality policies.

A commercially available SMT stencil printer was used for screen printing of the silver inks on polyester. Squeegees and flood bars were maintained with constant parameters throughout the study. The printed layers were dried using an in-line air flow convection dryer with infrared (IR) heating capability. Effect of dryer parameters on the print and electrical results were studied separately and optimized to its best performance. Metrological analysis was performed on the printed samples using high precision automated optical inspection system. Electrical measurements were conducted using a 61/2-digit high-performance digital multi-meter.

RESULTS AND DISCUSSION

The effect of the screen variables were first studied by analyzing the mean heights of the printed samples. Geometric shape profiles of the printed traces were recorded using the optical inspection system and analyzed in Minitab® statistical software. Figure 6 shows the main effect of mean trace height versus screen variables.

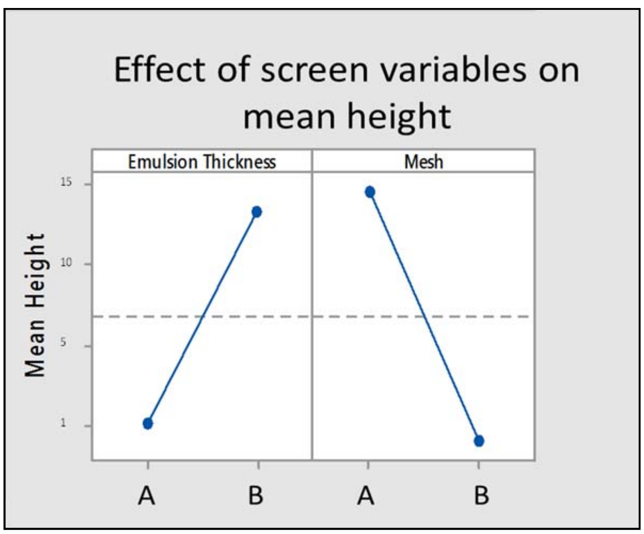

Figure 6. Effect of screen variables on mean height

It is observed that lower mesh count will have higher mean trace height compared to the higher mesh count. This is due to higher open area for the lower mesh count. It also showed that thickness of the emulsion is directly proportional to measured mean trace height. However, it is important to note that very high emulsion thickness decrease the mean height is anticipated as maximum ink transfer capability is approached. Resistance of the printed traces decreases as expected with increasing mean height. This was demonstrated by measuring the trace resistance as a function of screen parameters (shown in Figure 7).

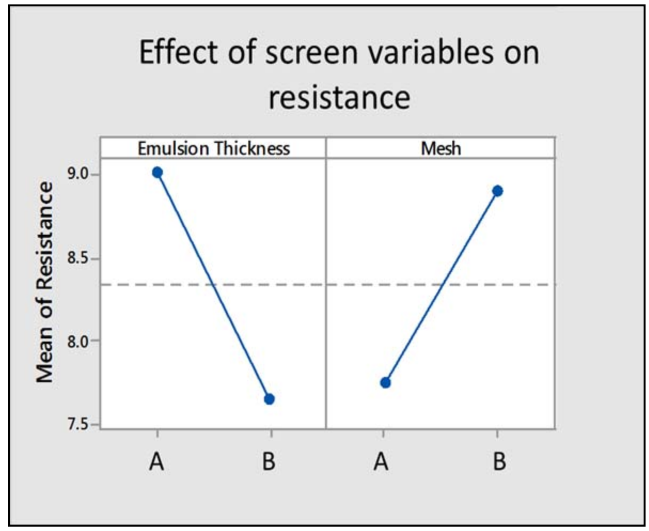

Figure 7. Effect of screen variables on trace resistance

Variation in the ink deposition and post dry trace resistance was then studied as function of the print process variables. Significant parameters such as print gap, print speed and print pressure were considered in this study. Settings of flood bar, snap off time was kept constant throughout this study. Figure 8 shows the effect of print process variable on the mean height of the printed traces.

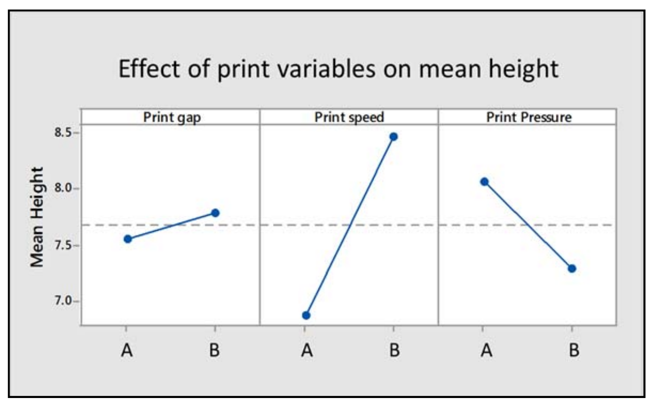

Figure 8. Effect of print variables on mean height

From these results, it was observed that the mean height is directly proportional to the print gap & speed and inversely proportional to the print pressure. This behavior is expected to be caused by ink shear. As the print speed increases, the shear rate on the ink increases which in turn reduces the ink viscosity and eases flow through the screen. This phenomenon is very much dependent on the ink viscosity range. For instance, low viscous inks should always be printed at faster speeds to prevent the dripping of ink from screen to substrate. Higher print pressures may result in scooping effect which reduced the overall mean height. Scooping effect is also dependent on print speed and squeegee direction. Higher pressure overall increase the screen and squeegee wear. Mean height of the printed traces also increases with print gap as the screen flexes more with higher print gap resulting in more ink transfer. The effects of the print process variables are also evaluated with respect to measured resistance. Resistance is lower for higher thickness and vice versa and shown in Figure 9.

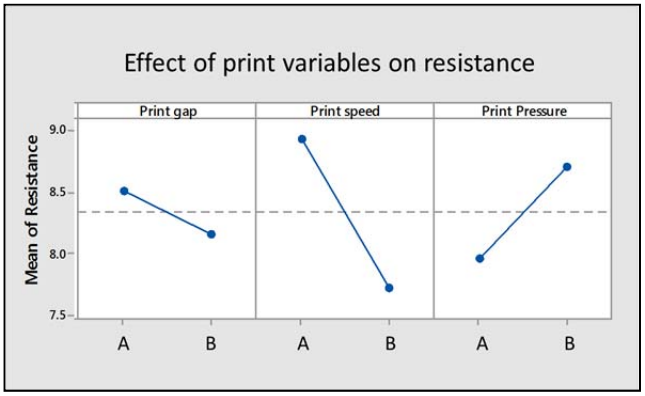

Figure 9. Effect of print variables on resistance

Effect of all the print process variables are highly dependent on the trace width. Even though trend in the responses are comparable, some parameters have larger impact than others in printing the very fine and wide traces. For example, higher print speed has a larger effect on fine traces compared to wider traces. A process window for printing the traces should be chosen to in order to minimize the negative impact from all the process parameters. From the statistical analysis of the data for different trace widths it is observed that process parameters will have less impact at wider traces compared to fine traces. Figure 10 shows the effect of trace width on mean height for a given screen parameters. It underlines that mean height tends to be quasi constant at the higher width compared to the fine lines.

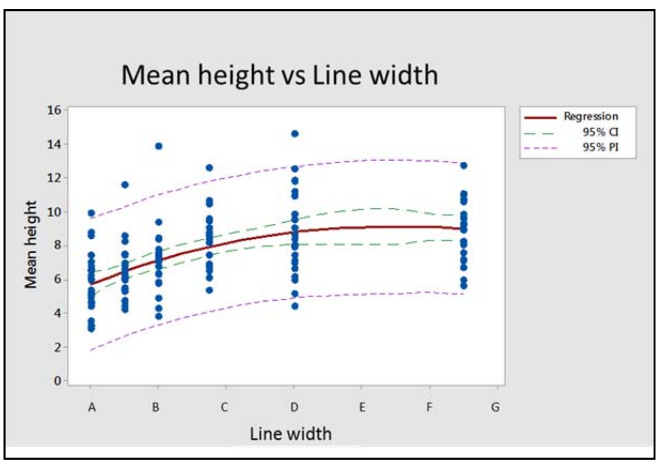

Figure 10. Effect of line width on mean height

The measured trace resistance in response to the line width for a given set of screen parameters is shown in Figure 11. It is demonstrated that both mean trace height and resistance are constant beyond a certain line width D. For this set of materials, screen and print parameters, there is fairly wide operating window to print traces exceeding the width D.

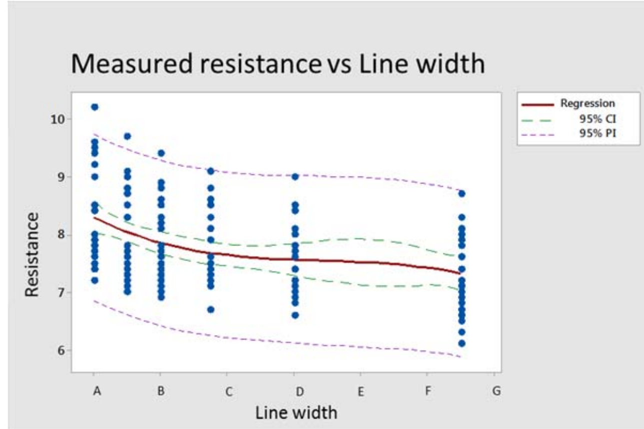

Figure 11. Effect of line width on measured resistance

CONCLUSION

This study focused on the screen printing of conductive inks on polyester substrates. Screen and print process variables have been evaluated as a function of ink film deposition and post dry resistance values. Limits for the process variables has been determined from ink supplier recommendations, combined with previous solder paste and graphics printing experiences. A usable operating process window for a given set of materials and parameters has been determined for the mass production of the printed electronics. Further research is underway to determine more refined process windows for different set of materials. Further in depth studies of the effects of mesh and squeegee materials is part of future research.

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