October, 2008,

Advanced Screen Printing - Practical Approaches for Printable & Flexible Electronics

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A series of advanced screen-printing processes have been developed to build functional high-density flexible electronic circuits. Not only do the single layer circuits have fine conductor traces, but also double and multi-layer circuits are connected by micro via holes with embedded passives and optical devices. Utilizing the whole process, an entire electronic circuit system can be built on a flexible substrate.

Introduction

Engineers once dreamed of building complete electronic circuits on a substrate using a simple printing process. Their dream turned into reality, and today is called the "Printed Circuit Board". The process has been refined to screen-printing conductive pastes on flexible substrates. In earlier years, the technology was limited to low-end circuits such as membrane switches for home appliances and personal computer keyboards. The reasons can be attributed to the low resolution of the process and low reliabilities from materials. The wet etching process with photolithography using copper clad laminates was chosen as the major manufacturing process for the fine and complicated printed circuit boards in the growing electronics industry.
However, the screen-printing process using conductive paste is much simpler compared to the wet etching process with photolithography as shown in Fig. 1 and Fig. 2. The only significant manufacturing equipment required is screen printers and thermal ovens. The investment for manufacturing lines could be much lower compared to photolithography and chemical etching of the copper foils.

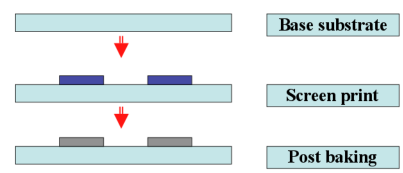


Fig. 1 Basic process of screen-printing

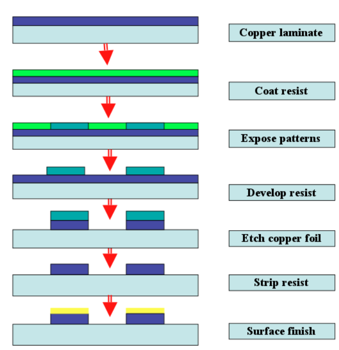


Fig. 2 Basic process of photolithography

Furthermore, the screen-printing process is capable of building more layers including insulation materials, resistance materials, dielectric materials for capacitance and more. Screen-printing process is capable to generate via holes between the conductive layers without drilling and copper plating; therefore, the screen-printing process provides great opportunities to produce low cost solutions for embedded passives with multi-layer circuits. The latest trials for fluorescent materials have produced flexible EL panels.

Some of the earliest flexible printed circuits were made by screening a conductive paste onto a dielectric base. However, there were reliability concerns noted from general consumer electronics products, which led to the adoption of photolithography on copper clad substrates as the industry standard. The screen-printing process produced lower resolution and the available conductive paste materials measured a much lower conductivity compared to the etched copper traces. Consequently, the process found success in areas limited to a few applications for consumer electronics.

In recent years a re-emergence of the printing process to mass produced electronic circuits gained popularity as the need to cut production costs continues to drive technical advances in the interconnect industry. Various processes including printing etch resists on copper substrates, dot matrix and screen printing conductive materials on dielectric base films were developed or refined. These processes are limited by the density they are capable of achieving in volume production.

Advanced Screen-Printing Technologies

A series of advanced screen-printing processes were developed as the basic manufacturing technologies for "Printable Electronics" in this study. An innovative technological concept named "Advanced Screen-Printing Technologies" was unveiled along with new manufacturing processes, materials and equipment. The new processes provides equivalent or even more capabilities to build complicated circuit constructions compared to the traditional subtractive process of copper foils or laminates with the photolithography. An optimized combination of the process condition and material is capable of generating 30 microns line/space on thin flexible substrates. Supplemental processes can generate 80 micron via holes for double sided and multi-layer circuits.

The basic steps for advanced screen-printing processes are the same as the traditional screen-printing process detailed in Fig. 1. A paste material is printed on a thin flexible substrate by screen-printing and then baked. If necessary, supplemental screen-printing is conducted on the conductor traces. The key feature of the advanced process is the optimized combination of the materials, screen-printers and screen masks. An optimized process condition generates 30 microns line and space on a thin, smooth substrate using an appropriate conductive paste. Printing machines and screen masks are already capable to screen-print 10 to 20 micron line and space. Research is underway to develop production quantities of conductive paste materials to realize the ultra fine conductors. Multiple RTR processing adds value to the advanced screen-printing process system by achieving low cost manufacturing for the valued flexible electronics.

Double & Multi-layer Process

Multiple printing processes with appropriate via hole technologies can produce double side and multi-layer circuits. Fig. 3 shows one of the via-hole generation processes for the double side circuits.

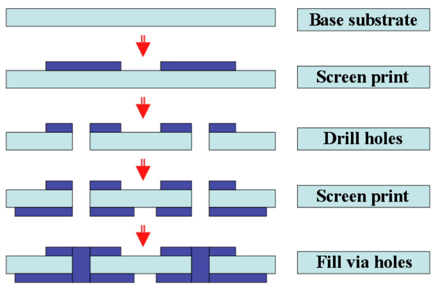


Fig. 3 Double side process with drilled via holes

First, a conductive paste is screen-printed on a thin plastic film as the first conductor layer. Second, small holes are drilled on the conductor pads. The piercing machine with a CCD alignment system minimizes the shifts to less than 20 microns. NC drilling and laser drilling are capable to generate equivalent micro holes on the thin films. The second conductor layer is screen-printed on the other side of the first conductor layer during the third step. Another screen-printing of conductor paste is added to form the via-hole and increases reliability.
Fig. 4 shows the build-up process of the advanced screen-printing by adding more conductor layers on the basic construction of the flexible circuits.

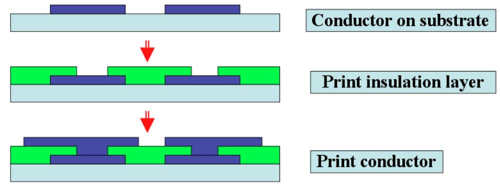


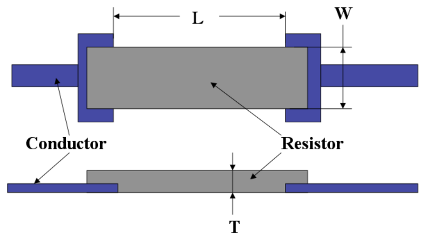
Fig. 4 Build-up process with printed via holes

An insulation layer is screen-printed on the conductor layer with small access openings followed by another screen-printing of conductor paste. Screen-printer with a CCD alignment system minimizes the shift between layers. There is no difficulty in building multi-layer constructions of up to 10 conductor layers by repeating the screen-printing processes of conductor layers and insulation layers.

Additional Functions by Screen-Printing

The advanced printing process creates more functionality compared to copper foil circuits produced by the traditional etching process. The printing process is able to produce not only conductors on substrates, but also insulations, capacitors, resistors, inductors and more as embedded components in the multi-layer circuits.

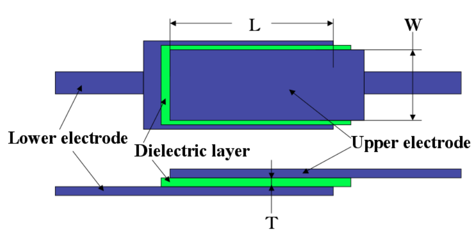
The resistor elements can be formed between two pads of the conductor layer by a screen-printing of high resistance material such as carbon paste as shown in Fig. 5.



$R = a * L / W * T$

Fig. 5 Construction of the printed resistor

Highly accurate resistors are made by high resolution screen-printing with suitable dimension control. The resistance value, R of the element is provided by the formula. The resistance of the conductor traces is provided using the same formula. The printing process provides a low cost solution instead of the etching process with special metal alloy foils as the resistance layer.
The capacitance elements require three steps of screen-printing on the conductor layer. The capacitance materials with high dielectric constants are screen-printed between the two electrodes as shown in Fig. 6. It is much simpler compared to the etching process with high dielectric constant laminates.



$C = b * \varepsilon * L * W / T$

Fig. 6 Construction of printed capacitor

There two kinds of structures to build printed inductors as shown in Fig. 7 and Fig. 8. The first construction uses drilled via holes through the base substrate films.

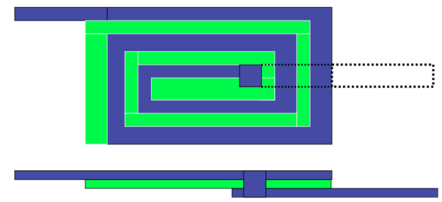


Fig. 7 Construction of printed inductance with drilled via hole

The second construction uses printed via holes on base substrate films. Multiple coils are formed with via hole connections to create larger inductances. The same processes can be repeated to generate higher inductances.

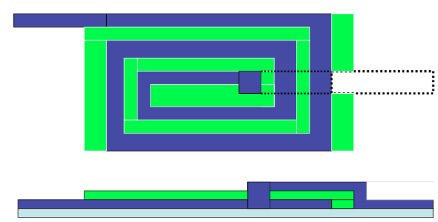


Fig. 8 Construction of printed inductance with printed via hole

To build functional electronic circuits on a thin film the advanced screen-printing process has to be repeated up to ten times. Exact dimensional control and alignment are required for both equipment and conditioning.

Printable Electronics Materials

Materials are key to high performance screen-printing, and are not limited to only conductive ink materials, but also base films, resistant materials, dielectric materials and more. The best performance is reached by using the appropriate combination of the materials. The results of using multiple combinations of materials for each layer in this study follows:

Base film: Polyimide, Polyethylene Naphthalate (PEN)
Conductor ink: Silver paste (Several compositions)
Resister ink: Silver paste, Carbon paste
Insulation ink: Epoxy resin, Polyester resin and Polyimide resin
Dielectric ink: Epoxy resin and Polyester resin with barium titanate powder

If necessary, a coating treatment is used to enhance the bond strength between the layers on the substrate or circuits prior to the screen-printing processes of materials.

Performances Examples

Several test patterns were generated for the evaluation of the printable flexible electronics. Fig. 9 shows one of the test patterns for the embedded passives with multi-layer flexible circuits. It has multiple fine conductor layers with micro via holes and also has embedded resistors, capacitors and inductors. Over ten screen-printing processes had to be conducted with accurate alignment to complete the whole electronic circuits on the thin film.

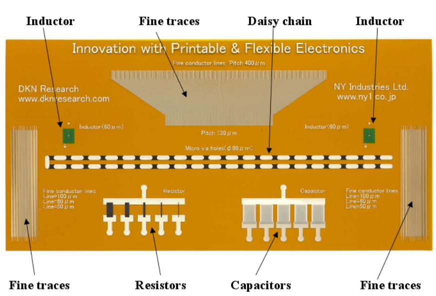


Fig. 9 Example of test sheet for embedded passive

Many combinations of materials in the test vehicles have been tried to achieve appropriate performance from the flexible electronic circuits. Heat resistant substrates such as polyimide film or PEN film are required as the base substrates to survive during the multiple high temperature processes.

The optimized combinations for the materials and process conditions yielded up to 60 micron pitch traces (30 micron line/spaces) on the thin substrates. Fig. 10 and Fig. 11 show examples of an IC substrate (130 micron pitch, 65 micron line/space) and a printed coil (100 micron pitch, 50 micron line/space) respectively.

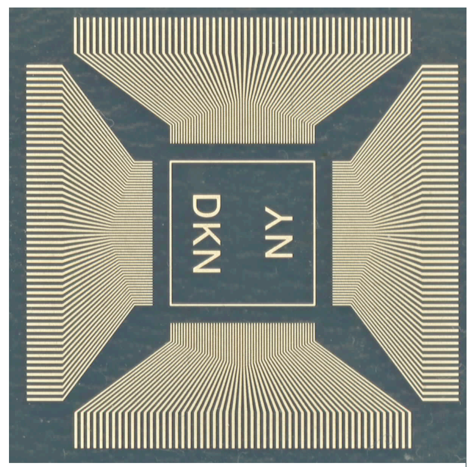


Fig. 10 Example of printed IC substrate (130 micron pitch)

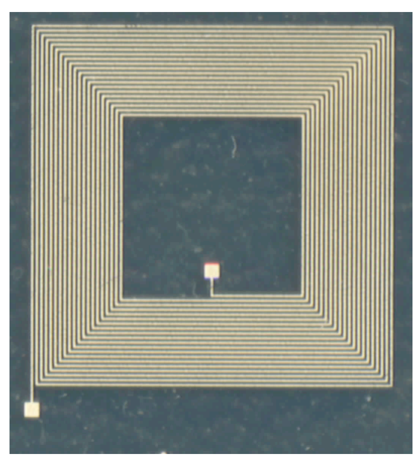


Fig. 11 Example of printed inductor (100 micron pitch)

Fig. 12 shows a cross section photo of the fine traces with 80 micron pitch (40 micron line /space) built on a 50 micron thick polyimide film. The cross section photo shows that the conductor thickness is smaller than 5 microns; however, the thin conductors have larger conductivities than traditional silver thick film conductors.

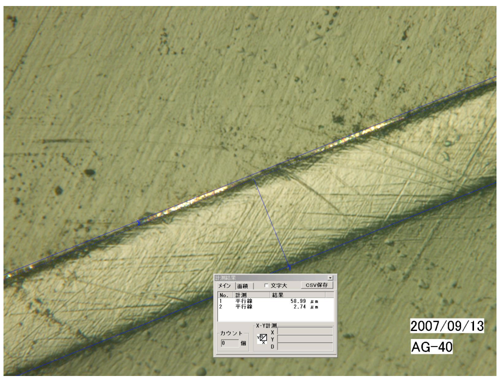


Fig. 12 Cross-section of fine traces (80 micron pitch)

Fig. 13 shows a cross section photo of the micro via holes made for the double side circuits. 80 micron diameter holes were produced by a micro punching process on a 50 micron thick polyimide film and filled with conductor paste using a dual screen-printing process.

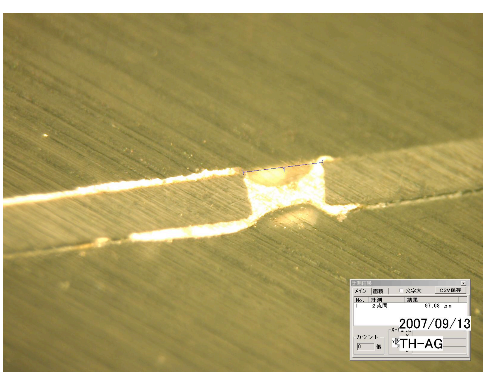


Fig. 13 Cross-section of drilled micro via hole (80 micron diameter)

The optimized combination between the hole shapes and conductor paste provide reliable via hole access using a simple screen-printing process.

Conductor Performances

Many electrical properties were measured for the test vehicles. Fig. 14, Fig. 15 and Fig. 16 show examples of the basic electrical properties.

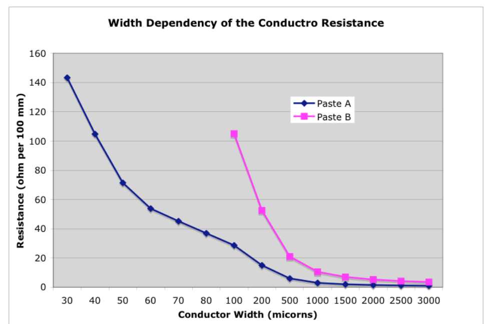


Fig. 14 Conductor resistance of printed resistors

Conductor resistances for fine traces are shown in Fig. 14. Paste B in the graph represents the printed traces made by a standard screen-printing condition with conventional silver paste. Paste B cannot provide narrower lines than 100 microns. Paste A represents an optimized combination of materials and substrates. A silver paste with special binder materials was employed for the trials. Paste A with appropriate substrates and process conditions is capable to generate 30 micron line/space on the thin substrates. The curves are very close to hyperbolic lines and are calculated by using the formula for the broad range of the line width down to 30 microns. The conductivity of the fine lines are very close to the theoretical limit of the conductivity of the paste.

Printed Resistors

Fig. 15 indicates the resistance of the printed resistors on the film at varying widths with the same length and thickness. The lines drawn on the graph show good hyperbolic curves, and are close to the theoretical values calculated using the formula. It indicates the advanced screen-printing process provide good accuracies of the printed resistors up to +/- 5% without supplemental trimming process. The hyperbolic curve indicates that one carbon paste ink provides one order range of the resistance by one time screen-printing. Multiple screen-printing will enable an expansion of the ranges of the printed resistors. Three times of screen-printing with different carbon base ink provides three orders range from100 ohm to 100 mega ohm.

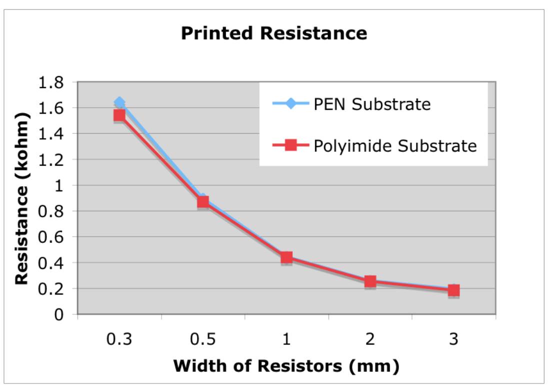


Fig. 15 Resistance of printed resistors

Printed Capacitors

The electrical performances from the printed capacitors with high dielectric constant materials at a frequency of 1 kHz are shown in Fig. 16.

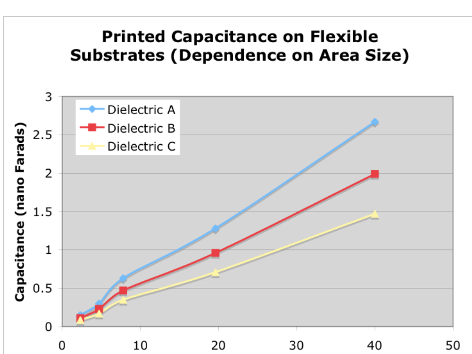


Fig. 16 Capacitance of printed capacitors

The dependency on the area size of the printed capacitors with a high dielectric constant shows high capacitance values with good linearity. It means that a 2 mm square printed capacitor can generate 200 pico Farads capacitance at 1 kHz frequency on the flexible substrates. The same construction generates 2 nano Farads in a 5 mm square space. Combinations of thinner dielectric and multi-layer construction will make the available capacitance ten times larger in the same sized space.

Printed Inductors

Fig. 17 shows an example of printed coils formed on a thin polyimide film. Multiple fine line screen-printings with punched via hole and printed via holes have realized a high inductance in a small space.

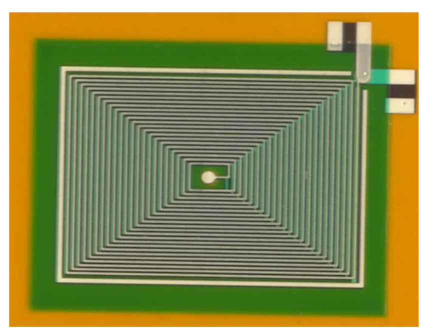


Fig. 17 Four layers coil made by screen-printing process

Flexible EL

Combinations of screen-printing from different materials including conductive ink, insulation resins with high dielectric constant and fluorescence material could generate a thin electronic luminescence patterns on a thin flexible substrate as shown in Fig. 18.

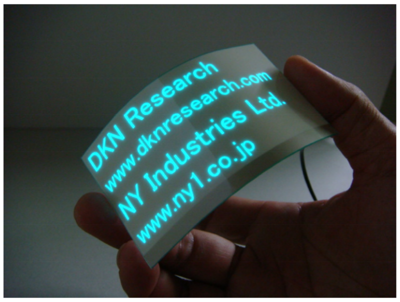


Fig. 18 Flexible EL formed by all screen-printing processes

Conclusion

Screen-printing is not a new technology in the printed circuit industry. However, the combinations of new paste materials and an advanced screen-printing process further increases the value of printable flexible electronics that cannot be made by the traditional photolithography process with copper foils. Additionally, more functionality from the circuits will be generated with new materials in the future.

The technical data evaluated in this study indicates that the advanced screen-printing processes are capable of generating high-density, multi-layer circuits on flexible substrates. They also indicate that it is possible to generate highly accurate embedded passive and active components in the flexible circuits.

Fig. 19 shows an example of electronic sensor module made by multiple screen-printing processes with different ink pastes. All passive components of the circuit were formed by the screen-printing process. The new silver paste makes soldering possible directly with the conductor; therefore the active components are assembled by a standard soldering process that is not available for the traditional polymer thick film circuits.

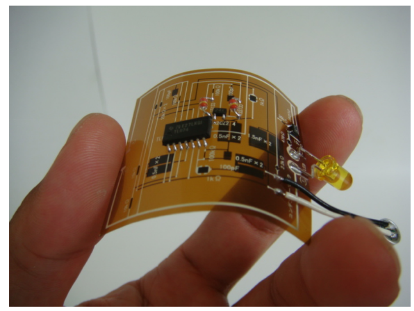


Fig. 19 Voice recognition module formed on thin polyimide film

Reference

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