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The Use of Inkjet Printing Technology for Fabricating Electronic Circuits – The Promise and the Practical

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Abstract
Manufacturers of electronic devices are always searching for new technologies that can improve processes, extend capabilities and lower costs. These drivers, along with the needs of new markets like Printed and Plastic Electronics, have brought processes like inkjet printing to the forefront. This paper explores the promise of what inkjet printing can bring to process simplification, cost reduction and improved capabilities. It also takes a critical look at the practical issues and concerns of this new technology.

THE DIGITAL FABRICATION PROCESS

Digital Fabrication refers to a process by which data in digital form is used to directly fabricate a part without intermediate tooling. In addition to inkjet printing, some examples of digital fabrication are: selective laser sintering, laser cutting, stereo lithography, laser induced printing and laser direct imaging.

Drop-on-demand inkjet printheads use either thermal or piezoelectric modes to eject droplets. Since most industrial fabrication is done with piezoelectric heads, this will be the focus for this paper. A typical piezoelectric head is constructed of a micro-machined chamber with one or more walls fabricated from a ceramic, such as PZT (lead-zirconate-titanate), which will mechanically deflect when an electric field is applied. The flexure of the wall creates a volume change within the chamber and an acoustic wave which drives a droplet of liquid through the hole in the nozzle plate. (See Figure One)

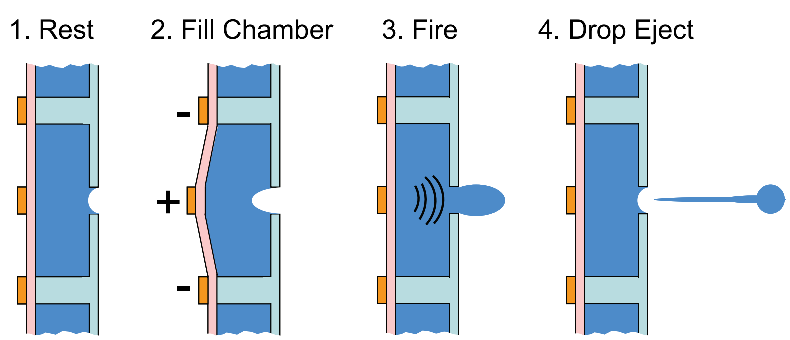


Figure 1 – Piezoelectric Drop Ejection

THE PROMISE OF INKJET PRINTING

Process Simplification and Faster Turnaround
The *promise* of inkjet printing is that it is an additive process, greatly reducing material waste as compared to a traditional lithographic process. The digital nature of the technique allows for direct CAD to board processing and in-process image compensation. Photomasks are eliminated along with the process costs and storage requirements. Inkjet printing is also a non-contact method (the head is placed about 1 mm above the surface during printing) and so is an ideal technique for fragile substrates.

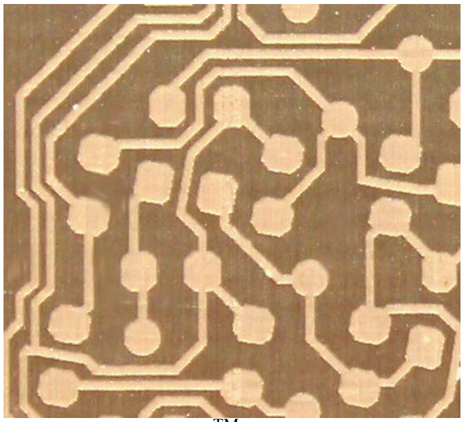


Figure 2 – LithoJet™ Inkjet Resist Printed on Copper

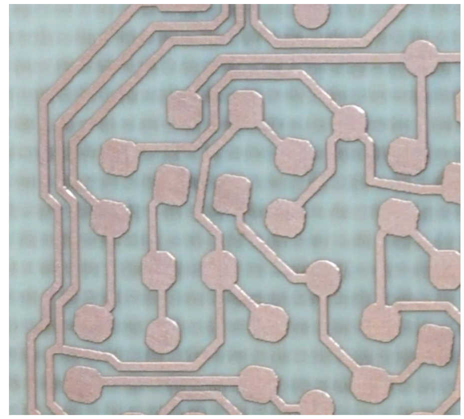


Figure 3 – After Etch and Strip

Waste Reduction

In addition to elimination of the photomask generation process, the downstream developing process step is also eliminated which can save on water, energy, waste treatment processes and maintenance down time. Overall it is a much more environmentally friendly process than traditional processes.

Inkjet imaging is inherently better environmentally than traditional lithographic techniques, in materials and processes. As an example, a dry film etch resist will be described.

For a standard dry-film process, the resist itself must be produced by casting the lacquer onto the polyester sheet from solvent carriers like acetone, alcohol or MEK. Dry film lacquer is 30% to 50% solids, meaning 50% to 70% is volatile organic content (VOC) that must be evaporated and treated, usually by burning. Even liquid photo-imageable (LPI) resists contain up to 60% solvents. Inkjet inks, like Dow's LithoJet™ inks for example, are 100% solids so no VOCs are evolved during manufacture or use.

When a dry film is used as an etch resist, approximately 50% of the material is developed away as waste. Inkjet ink is deposited only where it is needed, so the waste is minimal. In addition, the typical thickness of an applied inkjet ink is 10 to 15 microns, compared to 15 to 25 microns for dry film. Based on these numbers, an inkjet process uses only about 30% of the material of a dry film process, which is 70% less material to waste treat.

Dry film processes also requires photomask generation and resist developing, along with the associated water and chemical use, energy use and labor. Additional packagings such as boxes, plastic cores end supports and cover sheets add to the total material bill.

Improved Registration

Alignment of congruent images is a major challenge for PCB producers, especially for the soldermask process. The biggest potential advantage with digital imaging is the ability to correct for registration error due to distortion. In conventional contact imaging, you are limited to rigid body shift corrections (i.e. - X, Y and rotation). If there is any stretch, shrink or shear in either the mask or the substrate, getting the two patterns congruent, whether they are image-to-image or image-to-hole, becomes difficult. Some fabricators generate multiple masks with varying compensation factors in order to obtain a best fit. This, of course, is costly and time consuming.

A digital imaging system, properly outfitted with image capture cameras, is able to acquire fiducial positions and scale the data to fit. This could be done on a full panel basis or even on a board level within a panel. The maximum benefit would be realized when digital processes are utilized throughout the board building process.

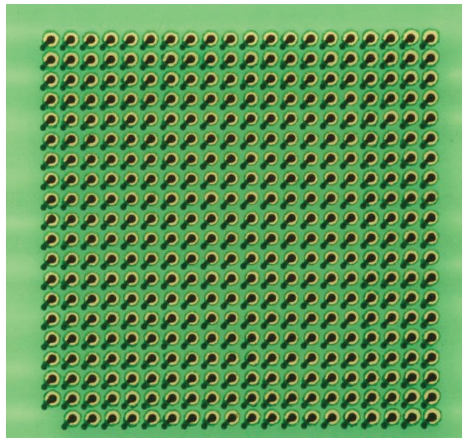


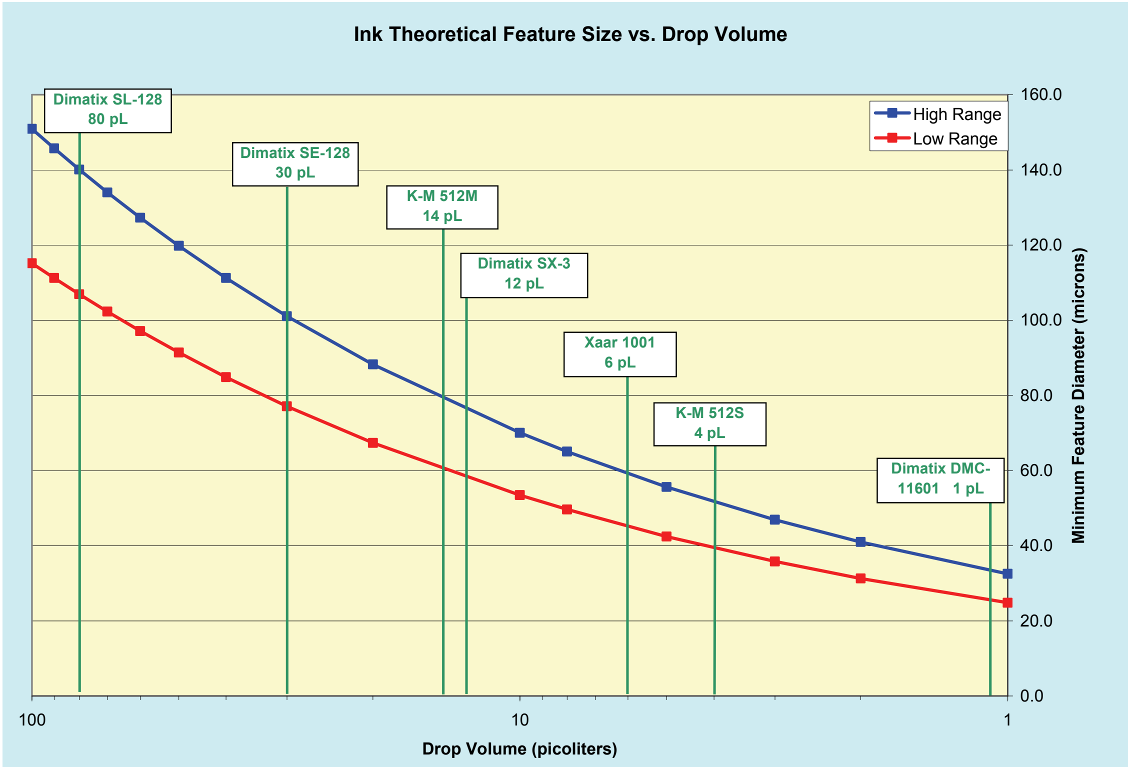
Figure 4 – Soldermask BGA Printed with Inkjet Masking

THE PRACTICAL OF INKJET PRINTING

The *practical* side is that inkjet imaging is a new technology with respect to circuit board fabrication and, like LDI before it, will take time to mature. Although inkjet-type printing was first developed in 1948, and home office and graphics printing has been mainstream for some years now [1], industrial digital fabrication is a complex process with more demanding requirements than just visual acuity. Magazines photos are printed at about 300 dpi [4], so for graphics applications this allows for less dense drop placement and faster printing speed. This is far from what is required for producing continuous and functional electronic circuitry. In addition, as resolution increases, the complexity of the deposition system increases whilst the printing speed decreases.

<u>Feature Resolution and dpi</u>

Two key parameters affecting the acuity of the final features are *drop volume* and *dpi* or drop spacing and overlap. Drop volume is a critical factor for minimum resolution of a system. Without special tricks, the finest printed feature can not be smaller than the drop diameter, and it is typically larger by some multiple. Graph One shows how feature size is related to drop volume with high-spreading and low-spreading inks plotted to show the interaction. Low-spreading inks have the potential to produce finer lines. The modification of substrate surface energy, through chemical or physical treatments can influence the minimum dot size possible, but usually with an impact on how much drop overlap is required for smooth lines. Additionally the use of “on-the-fly” UV pinning can be employed whereby a UV exposure system follows closely behind the printhead and partially cures the ink in place.



Graph One – Feature Size vs. Drop Volume – (Single Drop Diameter)

A certain amount of drop overlap is required for smoothing lines and is a function of the ink properties (surface tension, viscosity, molecular weight, etc.) and surface properties of the substrate (roughness, surface energy, etc.). Let us assume that a 33% overlap of droplets has been determined to produce a smooth line with a particular ink. (See Figure Five) Graph Two shows how inks with different spreading characteristics affect the minimum dpi required as a function of drop volume.

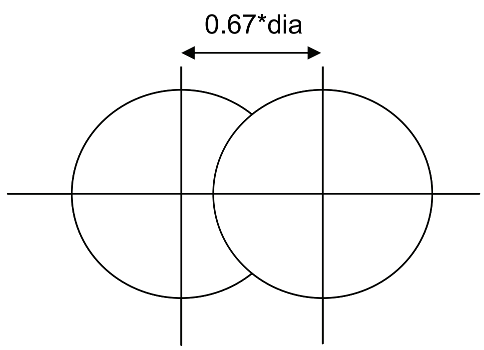
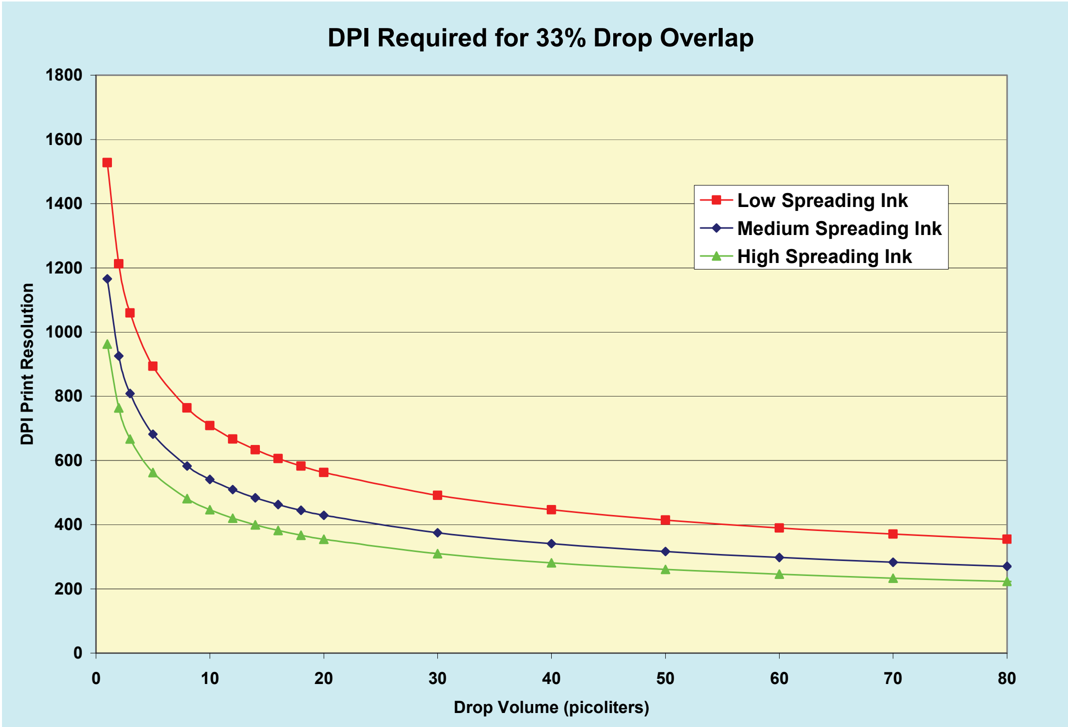


Figure 5 – Drop Placement with Overlap of 33%



Graph Two – DPI Required for Overlap vs. Drop Volume and Spreading

Depending on the spreading characteristics of the ink drops, the dpi will need to be adjusted to obtain the correct overlap. Increasing dpi in the scan direction is simply a function of increasing the firing rate, or frequency, of the printhead relative to the table speed. There are some limitations to the maximum firing rate due to head designs and ink properties, but for our purposes we can operate within an acceptable range without sacrificing speed.

Increasing the dpi in the orthogonal direction is more complicated and can directly affect printing speed. Each style of printhead has a fixed spacing of the nozzles, which is referred to as native resolution. For example, the Dimatix SE-128 head has 128 nozzles on a 508 micron pitch, which gives it a 50 dpi resolution. The only ways to increase this dpi is to make multiple passes, offsetting the head with each pass, or by adding additional heads that are interlaced. (See Figure Six) Often both techniques are used in combination such that multiple heads increase the apparent native dpi and multiple offset scans increase the final dpi. This increase in dpi, however, comes with a cost. Increasing heads means that the print system is more complex and a greater number of nozzles must be maintained through proper preventive maintenance so that drops are not lost. Increasing scans means more time is required for the multiple passes over the panel, so productivity is decreased. If smaller drops are used to produce finer features, then the number of scans will increase further.

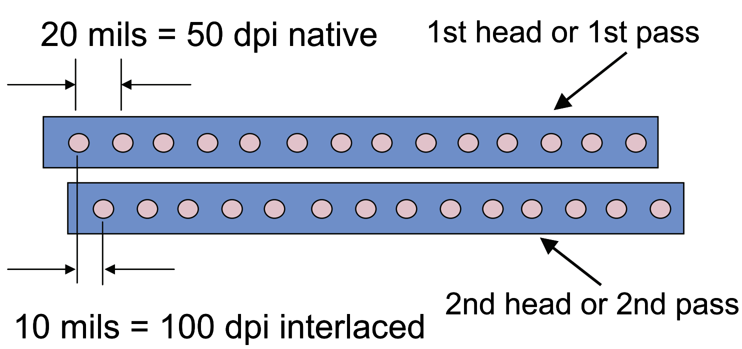


Figure 6 – Interlacing of Printheads

System Printing Speed

Resolution, printing speed and equipment complexity are intimately linked and understanding the trade-offs between these parameters is essential in making decisions about which system configuration best addresses a target application. The impact on printing time for one side of an 18” x 24” panel is illustrated in the following graphs. Graph Three shows printing time at 500 dpi and Graph Four shows time at 5000 dpi with changing conditions of table speed and number of printheads. The printheads here have a native resolution of 50 dpi. One can see that at 500 dpi, print times of less than one minute are possible with a reasonable number of heads: five. Increasing the dpi to 5000 causes the print time to increase by an order of magnitude, meaning a time of 5 to 10 minutes would be required.

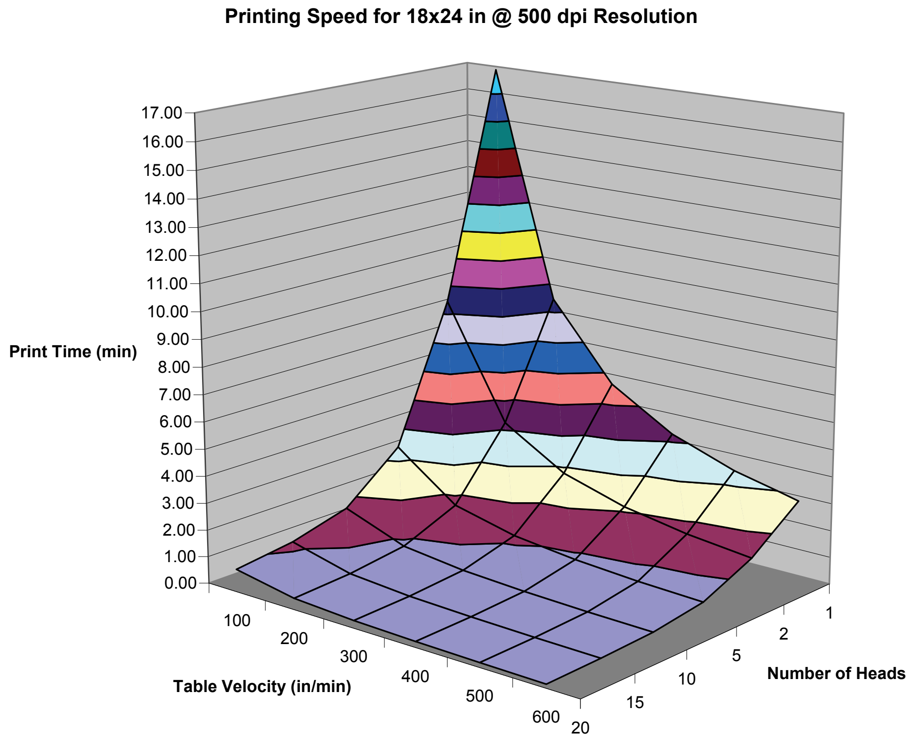


Chart Three – 500 dpi Printing Speed (Printhead=50 dpi native)

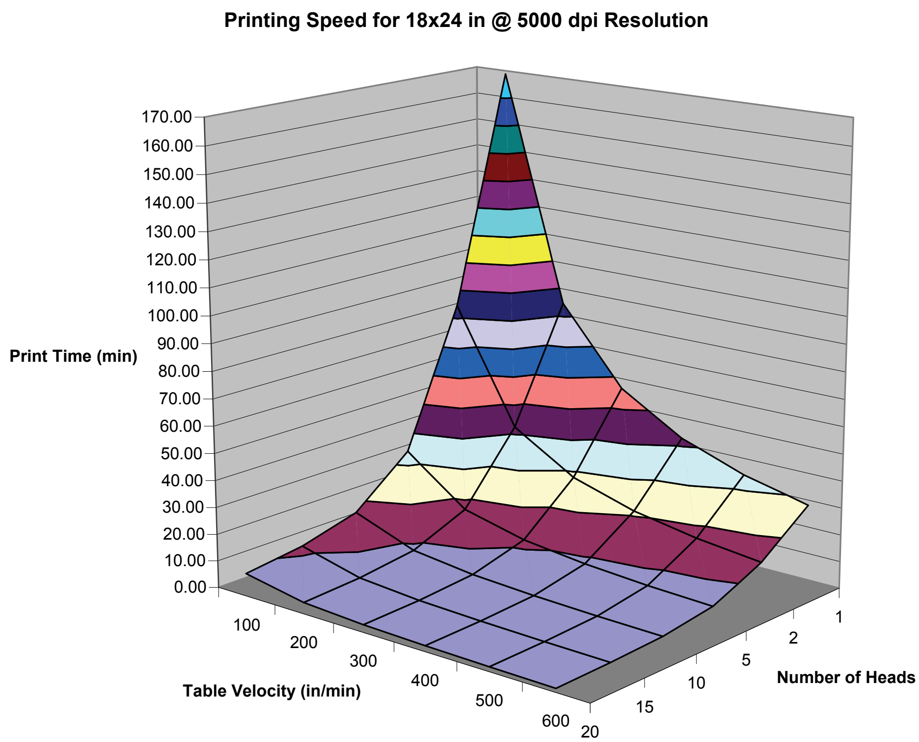


Chart Four – 5000 dpi Printing Speed (Printhead=50 dpi native)

Theoretical Printing Example

As an example, we can examine a theoretical case for imaging using inkjet. Using the following parameters, the printing speed can be determined:

Target Feature Size (Line / Space)	100 / 100 microns
Printhead Type	Konica-Minolta KM512
Printhead Drop Volume	14 pL
Native Resolution of Printhead (256 nozzles)	360 dpi
Print Width	36.1 mm
Printing dpi (X and Y)	2500 dpi
Table Scan Speed	3 m/min
Panel Size – Single-sided	460 x 610

Based on the desired dpi resolution, printing time for one side of the panel is calculated. Note that transport time and any alignment time is not included.

Required Firing Frequency (Scan Direction)	5 kHz
Required Scans with 1 Head	88 passes
Required Scan with 15 Heads	6 passes
Time to Print with 1 Head	~ 18 minutes
Time to Print with 15 Heads	**~ 1.2 minutes**

Ink Compatibility and Design

Interactions between the inks, the print heads and the system are paramount to the reliability of the process. For example, chemical incompatibility can damage print heads and reduce their useful life, or worse, create sporadic nozzle failures. Ink design is a complicated yet critical part of the system performance.

Most inkjet ink products for PCB applications fall into one of two general categories:

1) Hot-melt or Phase-change inks, comprised mostly of a wax-like material or,
2) UV-curable liquid type inks, with or without some volatile solvent.

Hot-melt or Phase-change inks typically freeze to a solid at a temperature between room temperature and jetting temperature. This process gives the simplest process sequence, since all that must be done is to jet the ink. It also has the advantage of being much less sensitive to the type of substrate onto which it is jetted; there is very little spreading of the ink as it cools. The drawback of this type of ink is that it is usually not as hard as a UV-curable ink, so it may be prone to damage in the subsequent processing. Also, because this ink softens at low temperatures (usually between 40C and 70C), it cannot be used for high temperature processes like $CuCl_2$ etching where process temperatures may be greater than 50C. The melt temperature can also limit the type of print head that can be used, since many heads are limited to a maximum of 55C.

UV-curable liquid type inks, once cured, have very good hardness and can withstand elevated temperatures, much like a dry film resist. The primary issue with a liquid ink is higher sensitivity to surface conditions of the substrate. Depending on the surface energy of the substrate and the surface tension of the ink, the amount of ink spreading can vary greatly. If a proper pretreatment can be found which is compatible with a specific ink, its use can enhance resolution. If no pretreatment is used, or if the surface has scratches or irregularities, as in a scrubbed surface, then spreading can be severe and unpredictable.

Dow's LithoJet™ inks use a different approach in ink design, combining the desirable attributes of both ink types. All of the inks are 100% solids, so there are no volatile organics evolved during processing. Although not truly a phase-change reaction, the cooling of the ink sets it in place within a short time after printing, allowing the ink to be pinned with very little spreading, regardless of surface conditions. The height and width of the ink deposit is dependent on the ink characteristics, substrate characteristics and print head capabilities (primarily drop size). Under the proper jetting conditions, these inks are capable of producing 75 um or less line and space patterns at reasonable printing speeds.

Conclusions

Inkjet fabrication equipment industry capable of producing features suitable for PCB production is becoming commercially available. The proper printhead and printing system, coupled with a suitable ink, like those in the LithoJet™ ink family from Rohm and Haas, can produce etched copper patterns for PCB production and do so with a lower environmental impact. (See Figures Eight and Nine) Printing times for a suitably configured inkjet system are in the range of traditional lithographic printing and, when coupled with the elimination of photomasks, make fast turnaround production especially attractive.

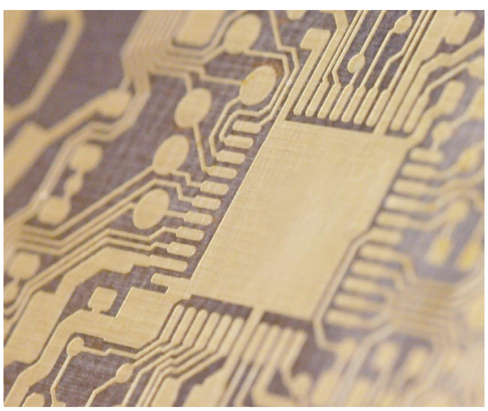


Figure 7 – Printed LithoJet Inkjet Etch Resist

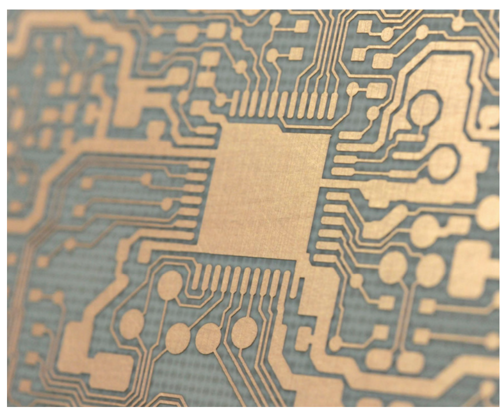


Figure 8 – After Etch and Strip

References

1. R. Elmqvist, Measuring instrument of the recording type, US Patent no. 2,566,443 (1948). S.L. Zoltan, Pulse droplet ejection system, US Patent no. 3,857,049 (1974), to Clevite Corporation.
2. Note: This is a very simplistic viewpoint because various classes of inks will respond differently. Phase-change inks, for example, will "freeze" quickly and not coalesce into a smooth line as easily as a liquid ink, thus they require a higher degree of overlap.
3. http://www.scantips.com/basics03.html Based on B&W photographs

Biography for Thomas Sutter

Mr. Sutter is currently researching new technologies and markets for electronic materials of Dow Electronic Materials. He has been with Dow, formerly Rohm and Haas, for over thirteen years. Prior to joining Dow, Mr. Sutter was a Technical Manager and Distinguished Member of Technical Staff at AT&T's printed circuit board manufacturing facility in Richmond, Virginia, USA.

Mr. Sutter holds a Master of Science degree in Imaging Science from the Rochester Institute of Technology in Rochester, New York. He has been involved with imaging processes for circuit boards and other electronics applications for over 25 years.

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