Manufacturing Printed Circuit Boards Using Ink Jet Technology

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Abstract

Ink jet (IJ) printing has long been talked about as a technique for manufacturing printed circuit boards (PCBs) in a fast and efficient way. This technology has now advanced to a point where legend printing, primary track imaging and soldermask application can now be achieved commercially. This paper describes advances in technology to enable application of the materials needed for primary track imaging and soldermask printing at the required resolution.

Introduction

Screen-printing and photolithography are the predominant methods of imaging in PCB manufacture. These techniques have served the industry well and provided the desired image resolution at an acceptable cost. Both methods have their own individual strengths and weaknesses. Manufacturers select the most appropriate process for their requirements in primary track imaging, soldermask application and legend printing. They suffer from the drawback of being analogue processes and require production of a screen or phototool. This adds cost and delays to the preparation of boards particularly for prototype and short run board production.

The benefits of digital imaging methods have long been recognized as a way to simplify, speed up and add flexibility to board production. Laser direct imaging (LDI) was developed in part to address this problem. LDI writes the circuit design on a special photoresist layer with a laser and thus eliminates the need to prepare a phototool. Additionally it provides excellent resolution but market acceptance has been limited by both capital and consumable costs associated with this technology.

IJ printing has long been talked about as a technique for manufacturing PCBs but it is only recently that commercial systems have become available.

This paper discusses the ink approaches and advances in both image resolution and ink performance to enable IJ technology to become commercially viable for primary track imaging and soldermask application. It highlights the advantages to be gained by adopting IJ approaches in PCB manufacture and some of the current limitations.

Why Use Ink Jet to Manufacture PCB's?

IJ technology has been widely adopted in many printing, patterning and related processes for three principal reasons:

1. It is a direct method to accurately place material in one step,
2. It is a digital process and thus affords the ability to write data and continuously change the output, without the need of any intermediate stages and
3. It provides a non-impact method to deposit significant quantities of material.

These properties make IJ ideally set up for introduction in to PCB manufacturing processes where the input has already been standardized as digital Gerber files and the translation of this data to the final product involves conversion to analogue imaging processes. Simplified IJ processes can be designed for many of today's board requirements and Figure 1 depicts a schematic IJ process to manufacture single sided PCBs.

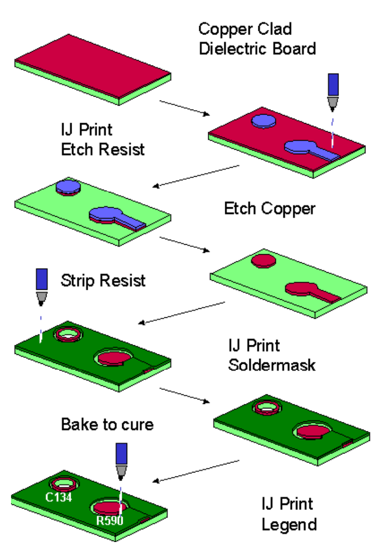

Figure 1. PCB Production Using IJ Printing

Existing blockers to the adoption of IJ technology in this application have been predominantly caused by two factors, the lack of available IJ printing heads capable of delivering the image quality and functional inks to perform the job. Substantial progress has now been made enabling IJ driven PCB production in an industrial environment.

Resolution Requirements in the Current Market

A market analysis of the existing and predicted track and gap requirements for different applications show line widths ranging from 1 to 12 mil (25-300 micron).

Most of the large volume, wide tracks (8-12 mils) are applied to paper and composite substrates using screen-printing techniques in China and other developing Asian countries. While this is a large segment by volume (approximately 45% by area), it attracts little value (15% by value). These relatively high volume run lengths, inexpensive and low performance requirements are well catered for using screen-printing techniques and little benefit would currently be gained by applying IJ technology.

The market for 4-8 mils is more interesting and covers the industry workhorse sectors of rigid FR-4 and multi layer boards up to about 10 layers. This segment of activity also contains both a sizable share of production volume (40%) and the majority of value (75%).

Sub 4 mil tracks are an important sector and will grow substantially in the future but currently accounts for low volumes (10%) and proportionate value (10%).

This analysis points to 4-8 mil (100-200 micron) tracks as the initial target sector worth addressing using IJ production technology and in future, 2-4 mil will become increasingly important.

DOD IJ Resolution Capabilities for PCB's

Resolutions achievable using DOD IJ printing are determined by a number of factors and any one of these can independently be the cause of image degradation. The most important are:

1. Drop size and drop reproducibility.
2. Drop spread on the substrate, and
3. The process used to place drops of ink.

1. Drop Size and Drop Reproducibility. The relationship between drop volume (in pl) and drop diameter (in microns) is shown in figure 2. Drops sizes achieved by today's leading heads (6-30 pl) are in the right order of magnitude (1-2 mils, 20-40 microns) to meet the requirements of the existing track and gap dimensions.

2. Drop Spread on the Substrate. When a drop is fired, the initial spherical shape (diameter d_1 in Figure 2) will deform as the drop hits (diameter d_2) and then settles on the substrate surface (diameter d_3) and this will result in a significant increase in diameter as depicted in Figure 3.

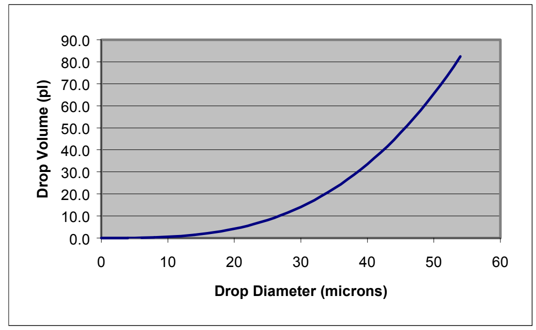

Figure 2. Relationship Between Drop Volume and Drop Diameter

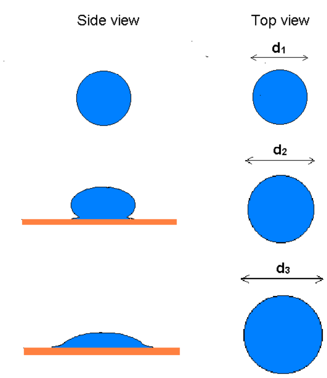

Figure 3. Diameter Increase on Printing

The extent of increase is dependent on many factors including, ink viscosity and surface tension, surface energy, roughness and absorbency of the substrate and the time taken to 'freeze' the ink. Unfortunately, ink viscosity and surface tension are fixed at relatively low values to enable correct functioning of the IJ head and this maximises ink spread. Control of drop spread is thus achieved by ensuring optimum preparation of the substrate and initial design of the combined ink and system to ensure rapid drop 'freeze'. By careful control of these parameters it is possible to minimise this spread to a factor of about 1.5 times the initial diameter (i.e. d_3/d_1). Failure here can result in 10 times diameter increases and give the appearance of rough edges as the ink 'wicks and feather' over surface defects.

3. The Process Used to Place Drops of Ink. The thinnest track can be formed by printing a single line of touching dots however this results in excessively wavy edges and more importantly would result in formation of gaps if errors occurred during printing. This problem can be minimised by placing drops on top of existing drops with an offset to smooth out the edges. IJ printers normally print the image by scanning the head backwards and forwards across the board and this introduces an additional complication that lines printed with the direction of the scan, at right angles to the scan and diagonally across the scan are different. This necessitates the need for a more complex and wider array drop pattern to minimize image imperfections. Mechanical and digital limitations also degrade the resolution possible.

In the real world, all these factors combine. Current state of the art printers use 30 pl drop size. For etch resist applications on rigid copper clad FR4 board a resolution of 8 mil (200 micron) track and gap is achievable in all print directions to produce high image quality and 6 mil (150 micron) features are obtainable with slight decrease in quality. This resolution is predicted to improve to 3 mil (75 micron) track and gap within the next year as equipment manufactures integrate smaller drop volume heads. This feature sizes place this technology as a real contender to compete with photolithography in the market.

IJ Ink Design for PCB Applications

Existing materials used in PCB imaging and soldermask application range from viscous fluids to semi-solid or solid gels when applied and solid after imaging and cure. This provides a dilemma for IJ where the ink must have a low viscosity and surface tension to be jetted. Several different approaches to deposit the required thickness of material using IJ have been considered for this market. A summary of the published approaches is presented in table 1 together with an assessment of some of the resultant strengths and weaknesses.

Table 1. Ink Types for PCB's Manufacture by IJ

Ink Type	Strengths and Weaknesses
Resin in volatile solvent with no cure	Difficult to build film thickness, copious amounts of solvent to remove, poor film performance and low image quality
Resin in volatile solvent with UV or thermal cure	Difficult to build film thickness, copious amounts of solvent to remove and low image quality
Aqueous resin with no cure	Difficult to build film thickness, difficult to remove water, poor film performance and low image quality
Aqueous resin with UV or thermal cure	Difficult to build film thickness, difficult to remove water and poor image quality
100% Hot melt with UV or thermal cure	Good film quality, moderate image quality but limited IJ head choice
100% UV cure	Good film quality, good image quality with rapid cure but difficult ink design

Significant problems have been encountered with all ink approaches based on lowering the viscosity of a resin by either making a solution or dispersion in an organic or aqueous solvent. No commercial systems are available, as these systems have struggled to obtain a film thickness of greater than a few microns verses the industry requirements of more than 10 microns from the dilute solutions required to give workable inks. No successful ways have been found to control ink spread before cure and this gives big drops which wick and puddle around surface energy variations and defects on the substrate resulting in unacceptable image quality.

More recently, a number of approaches have been developed, patented and commercialized based on '100%' inks. In these systems, all the jettable ink becomes the final film. These approaches enable the deposition of thick films, eliminate the need for solvent removal and provide the basis for functional, commercially viable products. Ink spread control is achieved by one of two mechanisms:

1. Hot melt inks, the viscosity is designed to be low in the IJ head and rise to become a gel or solid on cooling after landing on the board. Additional UV or thermal cure can then be undertaken later to obtain the final film performance. To date, the only commercial products of this type are legend printing inks.[1]

2. 100% UV cure inks work by having a low viscosity ink which is rapidly irradiated by UV light after hitting the substrate to effect polymerization resulting in solidification of the ink. Additional UV or thermal cure can then be undertaken if needed. Inks based on this approach have been commercialized for legend,[2] etch resist[3] and soldermask[3] applications.

Several manufactures have launched equipment based on these inks for legend printing[4] but only one is currently available for etch and soldermask application.[5]

Advantages and Disadvantages of 100% UV Cure Inks for Etch Resist and Soldermask

The combination of high resolution DOD heads, etch resist and soldermask inks and good system integration is now realizing the following advantages:

Direct digital processing, providing easy one-off to short run capability with ability to digitally modify the image for alignment and stretch on the fly.

IJ print and on line UV cure to eliminate the following stages: screen or phototool generation, screen printing or dry film lamination, exposure and wet development processing.

Savings on capital for equipment associated with the eliminated steps, reduced running and maintenance costs and space savings of this equipment's footprint.

Large reduction in material usage, particularly with etch resist as only the final track area get covered (typically 20%) versus the total board in existing processes, no dry film polyester backing film is used and chemicals are eliminated from the development stage. Reduced material usage also leads to reductions in effluent disposal costs.

Overall, the above benefits will lead to faster turnaround times at a lower production cost.

Disadvantages stem from using drops of ink to form the image and the consequences of being a different process to what industry currently uses. The main issues are:

Track and gap sizes are currently limited to 6 mils (150 microns) but this will decrease with smaller drop sizes.

The image generated consists of wobbly lines and rounded corner, compared straight lines and well-defined right angles when produced using photolithography. The effect that this will have for many end users is unclear.

Being a new technology, the number of inks commercially available is limited. These inks are general applicable but not optimized for some specific applications. This will change as technology adoption proceeds.

Etch Resist Inks for IJ Application

The existing 100% UV cure etch resist ink[3] has been designed to operate in a number of leading IJ heads, print on industry standard copper clad boards and then to be processed through the existing etch, strip and some plating baths. This strategy will enable trial and adoption of this technology by existing players for the cost of purchase or lease of an IJ printer together with the consumables used. Measured properties of the ink are summarized in table 2.

Table 2. Properties of 100% UV Cure Etch Resist Ink

Viscosity	12.4-14 cps at 40°C
Surface tension	25-28 dyne/cm (mN/M)
Cure conditions	Rapid UV cure
Film thickness	5-40 microns
Color	Blue
Etch chemistry compatibility	Ammoniacal etch Cupric chloride Ferric chloride
Plate chemistry compatibility	Resistant to acidic or neutral electroplating e.g. copper sulphate/sulphuric acid
Strip conditions	2.5-4% sodium hydroxide at 40-50°C and some basic solvent systems
Physical form of striped resist	Small flakes

Soldermask Inks for IJ Application

A similar design strategy has been adopted for the soldermask product[3] to enable direct ‘slotting in’ to existing production processes with a similar final performance to current soldermask. The ink utilizes 100% UV chemistry but requires an additional thermal bake to maximize the film performance in line with the conventional products for this application and to meet IPC SM-840C Class H standards. A summary of the soldermask properties generated using the IPC SM-840C protocols[6] with Avecia recommended fluxes is presented in table 3.

Table 3. Properties of 100% UV Cure Soldermask Ink[6]

Viscosity	9-10 cps at 40°C
Surface tension	28-29 dyne/cm (mN/M)
Cure conditions	Rapid UV cure followed by a thermal bake at 150°C for 1 hour
Film thickness	10-30 microns
Color	Green
Pencil hardness	5H
Tape adhesion	Pass on FR4, copper and gold
Solderability	Pass
Solder dip	Pass (copper, gold, 260°C, 10 s)
Dielectric strength	5500 V/mil
Resistance	$10^{12}\ \Omega$
Solvent resistance	Pass (isopropanol, isopropanol/water, limonene, monoethanolamine and water)
Hydrolytic stability	Pass (97°C, 90-98% RH, 28 days)
Machinability	Pass (drill, routing, sawing and punching)
Flame resistance	UL 94 V0 (>0.8 mm FR4)
Electrochemical migration	Pass (85°C, 90 RH, 10 V, 500 h)
Thermal shock	Pass (100 cycles -65°C to 125°C)
Moisture and insulation resistance	Pass (85°C, 90 RH, 24 h)
Fungal resistance	Pass (non-nutrient to fungi)

Conclusion

Progress that has been made in developing smaller drop size, DOD IJ heads together with new PCB market specific inks, has enabled equipment manufacturers to integrate these technologies and produce viable commercial IJ printing machines for the manufacture of printed circuit boards.

The current state of the art systems enables the formation of the primary circuit tracks, soldermask application and legend printing stages with large savings in lead-time, equipment requirements and chemical usage resulting in cost savings.

Resolutions that are available today can meet a large proportion of the markets need and this will increase further as the drop size decreases and finer features can be produced using IJ printing.

References

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3. Jetrack Etch Resist 001 and Jetrack Soldermask 001 inks available from Avecia Ink Jet Printing Materials, PO Box 42, Hexagon House, Blackley, Manchester M9 8ZS, UK.

4. Equipment suppliers for legend printing include: New System, Cabin, Mutoh, MarkFine, Printar, MicroCraft, Mivatec, Yokogawa and First EIE.
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Biography

Mark James received a BSc from Durham University and a PhD from University Newcastle upon Tyne, specializing in organic synthesis. After doing postdoctoral research at the University of Southampton he joined ICI and has remained there over the transformation through Zeneca to Avecia. For the past 8 years he has been involved in ink jet projects ranging from colorant design to developing solutions that enable PCB manufacture using IJ technology.