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# Direct Legend Printing (DLP) using piezoelectric inkjet technology

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Electronic Design Realisation

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# Direct Legend Printing (DLP) using piezoelectric inkjet technology

## 1 Introduction

The manufacture of printed circuit boards (PCBs) requires a complex multi-step process. One of the final steps of the process is the component identification (ident) lettering, which is called legend (or sometimes nomenclature) printing. The main driving forces for technological advances are cost and performance, and ongoing research and development has led to the production of more sophisticated (multi-layer) and efficient (better defined circuits and components) PCBs. The technique for legend printing, however, has hardly changed since the first production of PCBs. The silkscreen method, which is used almost exclusively for PCB legend printing, is the same technique that is employed to apply lettering to t-shirts.

Since its introduction in the mid-1970s[1], drop-on-demand inkjet printing has become the most widely used method for applying ink to paper. From small desktop printers attached to personal computers (PCs) to large area poster production systems, great improvements have been made in the drive electronics, head design and ink formulations of inkjet printers. Inkjet technology is now rapidly emerging as a leading digital imaging method for a variety of industrial applications other than ink on paper. Applications include 3-D graphic art, packaging, electronic and photonic device fabrication[2,3,4] and medical diagnostics and procedures.

The adaptation of drop-on-demand inkjet printing technology to legend printing of PCB panels systems has only become a viable alternative to silkscreen printing with the advent of jettable UV-curing inks compatible with improved piezoelectric print head designs[5]. Jetmask Ltd. has applied the technology to develop a single-step legend printer for PCBs. This paper presents aspects of the development of this system and compares the legend production to that of traditional silkscreen methods.

## 2 UV-curing inks

The ink is a critical component of ink-jet printing. Ink chemistry and formulation not only impacts the quality of the printed image, but also influences the drop ejection characteristics and the reliability of the printing system. The advantages of using a UV curable ink system, over conventional inks, for ink-jet printing, have been known for some time. UV-curable inks are environmentally friendly since they are 100% non-volatile and do not contain solvents (VOCs– volatile organic compounds). Their higher viscosity and fast, low temperature polymerisation curing gives improved adhesion to a variety substrates, resulting in a high quality cured print with far greater resistance to chemical and physical attack.

The basic components of UV-cured ink are monomers, oligomers and photoinitiators, although the ink also includes pigments, extenders and additives. The monomers (reducers) are the low viscosity components of the UV-ink, which influence the polymer structure, rheology and surface tension, curing speed, viscosity and chemical resistance. Oligomers in UV-inks are essentially high molecular weight acrylic resins which act as binders and determine the basic properties of the cured ink layer, e.g. flexibility, adhesion, hardness and chemical resistance. The photoinitiators absorb U.V. energy resulting in an ionisation of the molecule into extremely reactive free radicals. These free radicals initiate the polymerisation reaction resulting in a fully cured film. The concentration and wavelength specificity of photoinitiator is thus important in determining the curing speed and level of curing.

Many factors, such as ink-jet print head capability, photoinitiator and low-toxicity monomer & oligomer availability, had hindered the progress of UV curable ink-jet ink development. Today, however, commercial UV-inks with the requisite UV photoinitiators, oligomers, monomers etc., to give suitable surface tension, viscosity, surface-to-bulk photoinitiator ratio, are readily available. Further, UV-ink development is on going for ink optimisation in relation to print head design and application specificity[6].

## 3 Piezoelectric inkjet technology

The basic principle of piezoelectric drop-on-demand inkjet technology is the ejection of fluid droplets from nozzles, termed a print head, by a pressure wave created by the actuation of piezoelectric material, on the application of voltage pulses. Suitably bonding the piezoelectric actuator to an ink-filled cavity, results in an expansion or contraction in the cavity volume due to the mechanical displacement of the piezoelectric, creating a pressure wave in the ink. This pressure wave travels through the fluid into the nozzle bore resulting in the ejection of a specific column of fluid. Due to pressure wave reversal at the nozzle, after the drive pulse has completed the pulse cycle, the fluid in the nozzle bore begins to retract whilst the ejected fluid column travels away from the nozzle with a specific momentum, dictated by the kinetic energy of the droplet. Under optimum conditions the result of this action is the separation of a fluid packet, which possess a detachment tail (ligament) and that subsequently forms a drop due to surface tension effects providing that the spacing between the nozzle and the substrate surface is large enough. The velocity of the ejected drop is directly related to the kinetic energy induced in the drop by the pulsed pressure wave. This process is depicted in Figure 1.

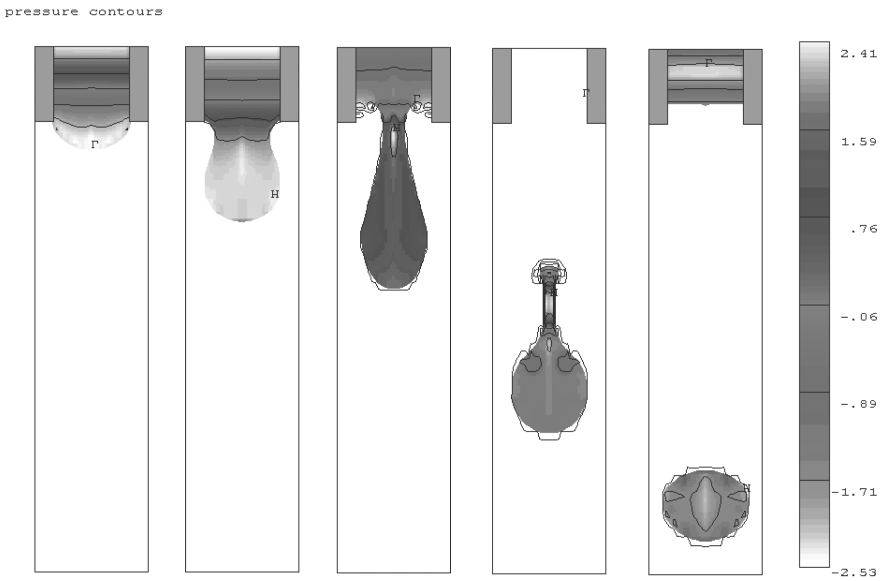


**Figure 1: Piezoelectric pressure induced ink droplet ejection**

The most commonly used piezoelectric material in print head manufacture is PZT (lead, zirconate titanate) ceramic, which can be employed in a number of operating modes. Bend, push and shear design principles have been successfully implemented in many commercially available print heads. During manufacture, the PZT is poled and then electrodes are placed on the surface of the PZT. In both the bend- and push-mode designs, the electric field generated between the electrodes is in parallel with the polarization of the PZT. In practical implementation, a thin diaphragm between the PZT and ink is incorporated to prevent interactions between them. In shear-mode, however, the electric field is applied perpendicular to the polarization of the poled PZT employing interdigitated or planar electrode configurations. The shear action deforms the PZT against ink to eject the droplets. In this case, the PZT becomes an active wall in the ink chamber and interaction between ink and PZT is an important aspect of a shear-mode print head design.

Although the piezoelectric print head operating principle is simple, the engineering required is very complex. Irrespective of piezo operational mode, one of the most critical components in a print head design is its nozzle. Nozzle geometry such as diameter and thickness directly effects drop volume, velocity, and trajectory angle. Variations in the manufacturing process of a nozzle plate can significantly reduce the resulting print quality. In general, the deformation of a PZT driver is on the sub-micron scale. For a large enough ink volume displacement to allow drop formation, the physical size of a PZT driver is often much larger than the ink orifice. Therefore, miniaturization of the piezoelectric ink-jet print head has been a challenging issue for many years. The drive electronics has been an important aspect of this. Factors such as drive pulse shape, drive-pulse mark-space ratio and droplet ejection frequency are key. Other engineering considerations include, the operational ambient pressure of the print chamber or processing zone, the ink cavity geometry and the ink pressure head.

 

The availability of ink-jet print heads with the capacity to reliably deliver more highly viscous UV-curing inks has only recently become a reality with the improvements in the design of piezoelectric inkjet print heads. Shear mode piezoelectric print head design, has been found to generate a greater deformation in PZT than direct mode when the same field is applied[78] and this piezoelectric technology, pioneered by Xaar plc[9], has proved most successful for use with UV-curing inks[10]. Thus, the effect of issues such as ink delivery and nozzle geometry on reliable and reproducible performance, along with the need to achieve high nozzle density, high speed print heads has been the primary focus for investigating shear mode OEM print heads for our DLP printing system.

## 4 Direct Legend Printing (DLP) process development

The design of the Jetmask single step direct legend printing (DLP) system has required the understanding and implementation of a combination of several technologies from the engineering and physical sciences to configure OEM print heads to reliably print good quality legend onto PCB panels, using commercially available UV-curing inks. Figure 2 shows a flow chart of the DLP development process, which is discussed in the following sections. Development programs have focussed on key issues such as the reliable and accurate placement of drops onto the substrate, control of the fluid interaction with the PCB surface in order to achieve good image definition, consistent, fast UV curing of the materials and the nature and quality of the solidified legend features. The detailed process parameters are already the subject of a number of patent applications[11].

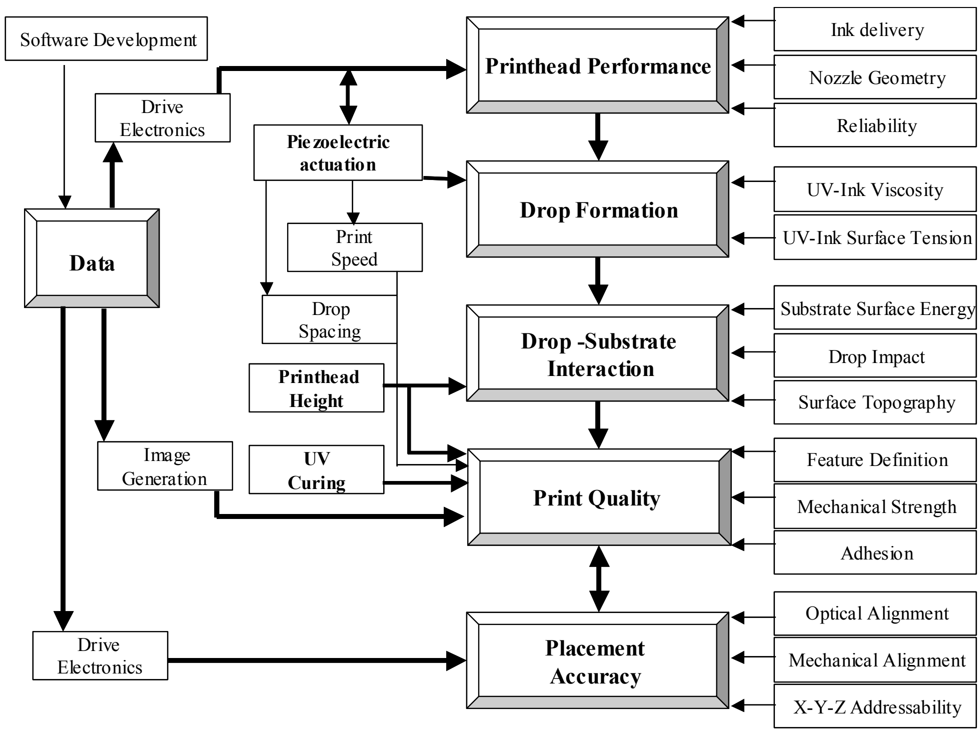


**Figure 2: DLP process development flow chart**

Legend feature quality relates to image definition, (placement accuracy and surface interaction behaviour), adhesion, and mechanical integrity, which is a function of the droplet generation, ink-surface impact dynamics behaviour and curing (solidification) of the ink. The detailed understanding of drop placement accuracy as a function of printing mode and print speed, liquid droplet impact and interaction with the substrate surface and curing is, therefore, of major importance.

## Ink–substrate interaction

A high velocity spherical droplet, as produced by a drop-on-demand ink jet print head, colliding with a solid surface induces droplet deformation resulting in the generation of a lamella that spreads radially out from the point of impact producing a shock front rim that expands to a maximum diameter. At the maximum the liquid front rim continues to spread but at a reduced rate (complete wetting), stays at rest, or retracts toward the point of impact dependent upon the wetting and impact conditions involved. The difference between the solid surface energy and the fluid surface tension coupled with the geometry and momentum (mass x velocity) of the droplet affects the energy loss dynamics. Thus, spreading (wetting) relates to the physical and chemical interaction of the liquid ink with the substrate and depends on how the droplet liquid front evolves due to the impact energy and droplet properties, and how much of the drop's mass transfers into the media (due to such mechanisms as wetting, absorption, diffusion, wicking and swelling). Factors that influence this include droplet velocity, dynamic viscosity, liquid density, and static contact angle (differential between ink surface tension and substrate energy).

The droplet velocity is a function of drive pulse wave shape & print head height above the substrate. **Surface** tension (wettability) is the energetics of a liquid arising from unbalanced molecular forces at or near the **surface.** The surface energy of a solid is intimately related to surface chemistry and morphology. **Surface tension and surface energy is normally** measured in dynes/cm (mN/m), where a dyne is the amount of force required to produce an acceleration of 1cm/sec on a mass of 1g. In general, if a liquid has a surface tension lower than the material's **surface energy**, then it will spread out over the **surface** in a uniform wet layer. If the ink's surface tension is equal to or higher than a material's dyne level, the liquid will become cohesive and tend to remain in droplets.

## Ink–substrate interaction assessment

Computational fluid dynamic (CFD) modelling permits the simulation of a wide range of process permeations relating to the droplet generation and ink drop-substrate interaction process, particularly in respect of ink free surface properties. The software also enables changes to be made to the printing geometry, print environment, and droplet size and impact velocity.

Flow Science Inc's *FLOW-3D*®[12] CFD modelling software was used to create both 2-dimensional and 3-dimensional images (see for instance, Figure 3) that permitted visualisation of the printed legend construction, under various process conditions. High speed CCD imaging was then employed to record, in real-time, the behaviour of ink ejection, droplet creation, surface impact and spreading, dot coalescence and UV curing. Such images provided valuable data to validate the computational modelling predictions.

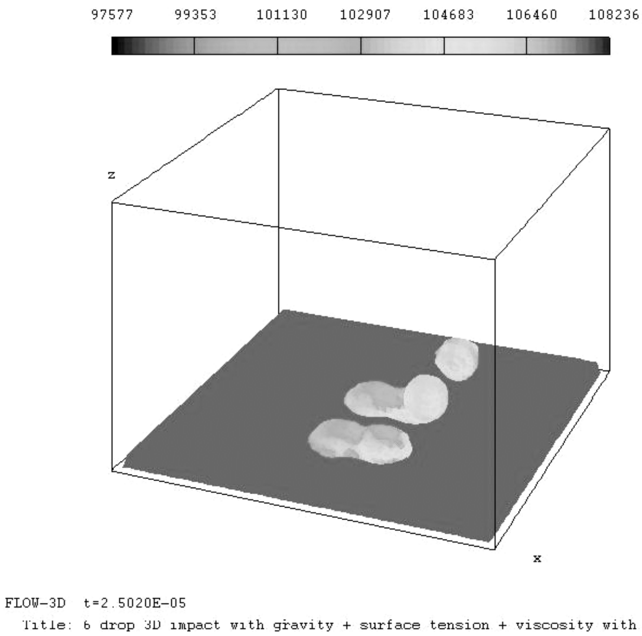


**Figure 3: CFD 3-D simulation image showing droplet spreading and the influence of drop coalescence**

CCD imaging was also used to collect static contact angle measurements. Contact angle measurements correlates to the wetting or non-wetting of a solid by a liquid due to ink surface tension and substrate surface energy difference. It is the angle included between the tangent plane to the surface of the liquid and the tangent plane to the surface of the solid, at any point along their line of contact. High substrate surface energy favours low contact angle behaviour concomitant with extensive spreading of the liquid.

Using UV-curing ink, contact angle measurements were made on a variety of PCB laminates (rigid and flexible), in various stages of production. Further, surface energy measurements of these PCB laminates were carried out, using Sherman Treater indicator pens. The assessed surface finishes included: bare laminates, standard copper finish and solder mask with various treatments. The Sherman Treater indicator pen is not a precise method; it relies on observations of the non-wetting behaviour of a layer of fluid of known surface tension when applied to the substrate. However, combined with contact angle measurements, it proved to be a good quality control method for assessment of surface treatment and served as a reference to allow definition of the process envelope.

Surface roughness measurements were carried out using Dektak profilometry and optical interferometry. Clear differences were found due to the influence of the underlying fibres parallel and perpendicular to the warp direction. In general, for rigid boards, a regular structure can be observed in one axis whilst perpendicular to this there is a more random structure. Flexible material tends to have a random structure in both directions. This can have a significant affect on surface wetting. For instance, the ink will spread along a weave direction if not otherwise controlled by process methods such as rapid curing. Although, this affect was found to be less significant once the solder resist is in place.

Properties such as print quality, adhesion and line width have been related back to ink properties and initial surface conditions. The UV-inks studied, with viscosity in the range of 20–30 cps and surface tensions of 20–25 mN/m, (dyne/cm), gave substrate surface energies in the range of 30–50 mN/m on the various PCB surfaces, and contact angle measurements between 25–40°. In general, the lower the substrate surface energy, the less the fluid spread, however this is complicated by the influence of the surface roughness. Smaller contact angles promote ink spreading whilst greater contact angles can induce the occurrence of surface tension driven line breaks during printing.

## UV curing

UV curing is a critical parameter in determining the print quality and the physical properties of the printed legend features. The development of the intended properties depends on the design and management of the UV lamp. The four key factors are: UV irradiance (or intensity), spectral output (wavelengths) of UV, dose (or time-integrated UV energy), and infra-red radiation[13].

Inks exhibit very different response to peak irradiance or dose, as well as to different UV spectra. Thus, the ability to identify the various lamp characteristics and match them to the optical properties of the curable ink, is very important for an efficient production process. The optical characteristics of the curing system, which affect curing, include spectral absorbance, reflectance and scattering, optical density and infrared absorption. Spectral Absorbance is the relative energy as a function of wavelength absorbed in the material at increasing depth. Total spectral absorbance includes all contributions from photoinitiators, monomers, oligomers, and additives, including pigments. Reflectance and scattering is light energy, which is "redirected" by or within a material, rather than absorbed; typically caused by the substrate material and/or pigments in the curable material. Optical density relates to the opacity (colour strength) and thickness of a film. These factors all affect the amount of UV energy available as it passes into and through the curing material. Infrared (IR) energy absorption from the UV lamp, is the principal source of heat to the surface temperature, which can also have a significant effect on the curing reactions.

A typical UV bulb consists of a quartz glass tube filled with various blends of mercury and other chemical compound. The contents (fill) of a lamp determines the UV spectral output, which is the intensity of light at each wavelength over the range of wavelengths emitted by the lamp A standard mercury (Hg) arc lamp emits light in both the short wavelength and long wavelength with strong emission lines at 254 nm, 300–320 nm and 365 nm. UV lamp spectral output can be altered by the inclusion of metal halides. Iron doping shifts the lamp output to the 320–390 nm range and gallium doping to the 390–410 nm range. All components in an ink formulation absorb UV radiation. Photoinitiators absorb and are activated by wavelengths around 250 nm. and 365 nm. The oligomers and monomers absorb UV energy at 200–260 nm. For pigments, absorption depends on colour. Dark pigments have strong absorption in the UV range below 320 nm, black pigments absorb throughout the UV region, while white pigmented systems absorb most UV energy and reflect most visible energy but have a transmission window at approximately 390–420 nm. Thus, curing efficiency relates to the ability of the lamp to effect photoinitiator activation in the presence of a high percentage of other non-initiator materials that absorb the UV light.

The irradiance of a UV lamp is the radiant power arriving at a surface per unit area ($W/cm^2$), which incorporates all of the contributing factors of electrical power, efficiency, radiant output, reflectance, focus, bulb size, lamp geometry and distance to the surface. The intense, peak of focused power directly under a lamp is referred to as 'peak irradiance'. Dose (and time) relates to the accumulated energy to which a surface has been exposed and is inversely proportional to speed under any given light source, and proportional to the number of exposures. Infrared radiance is the amount of infrared energy primarily emitted by the quartz envelope of the UV source. This energy is collected and focused with the UV energy on the work surface, depending on the IR reflectivity and efficiency of the reflector.

All these factors have been investigated to determine the parameter window for an optimal UV curing process. The key parameters were found to be UV curing initiation time after impact, radiation intensity and wavelength, and exposure time. Figure 4 shows measured lamp intensities as a function of distance. Best results have been obtained using a 2 stage process with an Hg arc lamp. Stage 1 is a low intensity tack cure used to control image quality by reducing ink spread on the substrate surface. The time between drop impact and onset of UV curing is a critical parameter in producing accurate and well-defined images. Stage 2 is a high power UV bake to complete the curing process, which can be varied in intensity and time to optimise cured material properties such as adhesion onto different substrate surfaces.

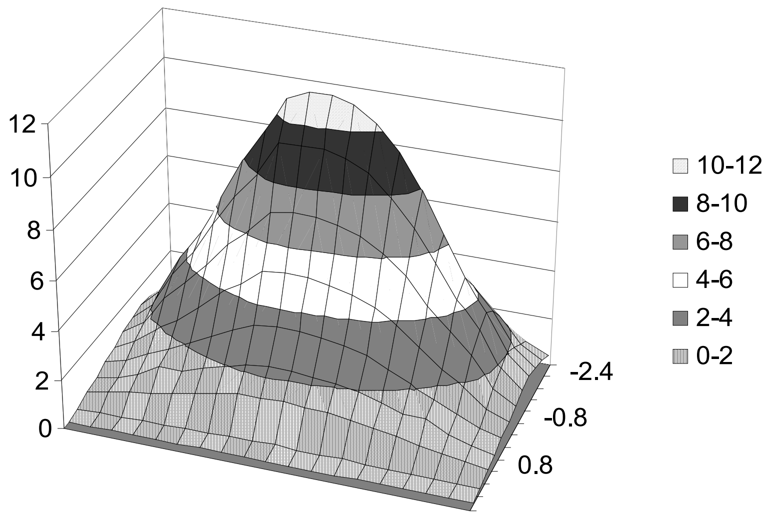


**Figure 4: Plot of UV lamp intensity as a function of distance**

## 5 Print quality

Besides UV-curing, other key print process parameters were found to be drop volume, print speed, drop spacing and print head height above the substrate. Exhaustive experimentation were carried out to assess the influence of print head height on drop placement in considering various possible jetting errors (for instance, ejection cone angle error that is nozzle geometry, ink, and pressure wave shape specific), variation in drop speed and timing of drop ejection. Print head heights of between 1.5 and 2mm were found to be optimal. The system does, however, have surface topography tolerance. For instance, if the circuit is a flex-rigid with large steps across the surface, the system can cope with the extra print height in the thinner panel areas at the expense of some slight image degradation if the effective print height increases beyond a few mm's. Figure 5 shows the present Jetmask process envelope relating to feature heights and widths, drop volume and print resolution.

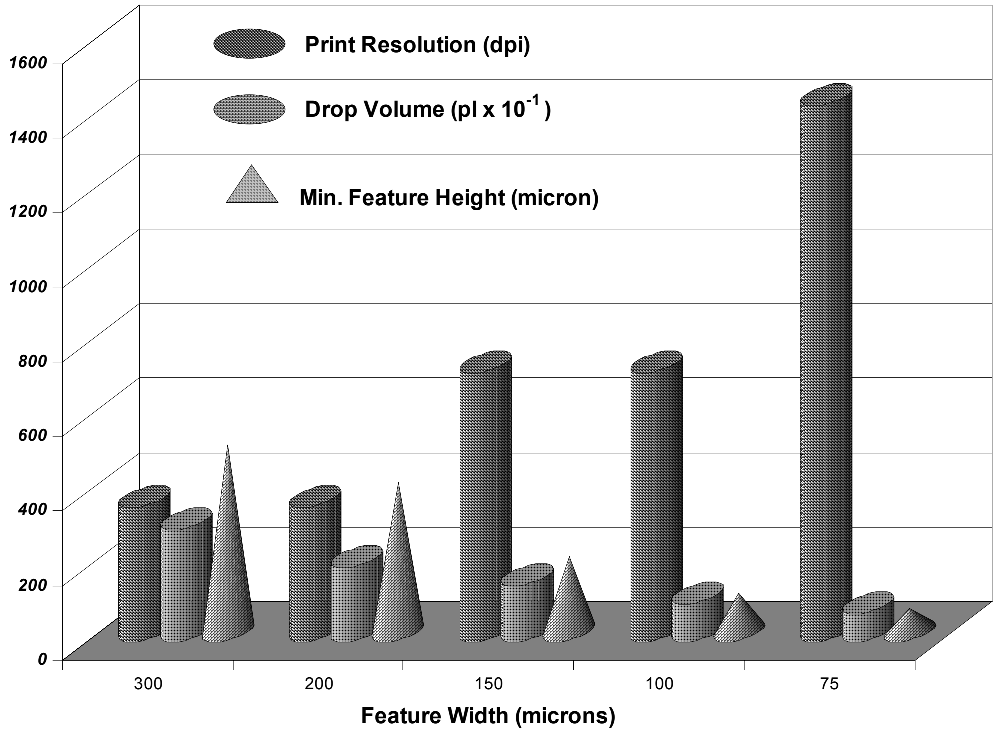


**Figure 5: Process envelope relative to feature width and height, drop volume and print resolution**

Print quality was monitored by visual examination using optical magnification, which included scanning electron microscopy (SEM). Figure 6 shows optimised printed features at low & high magnification, while Figure 7 is a SEM micrograph showing the intimate contact of an inkjet printed UV curing ink ident feature on solder mask surrounding a copper pad.

 


**Figure 6: Jetmask DLP legend features at low and high magnification**

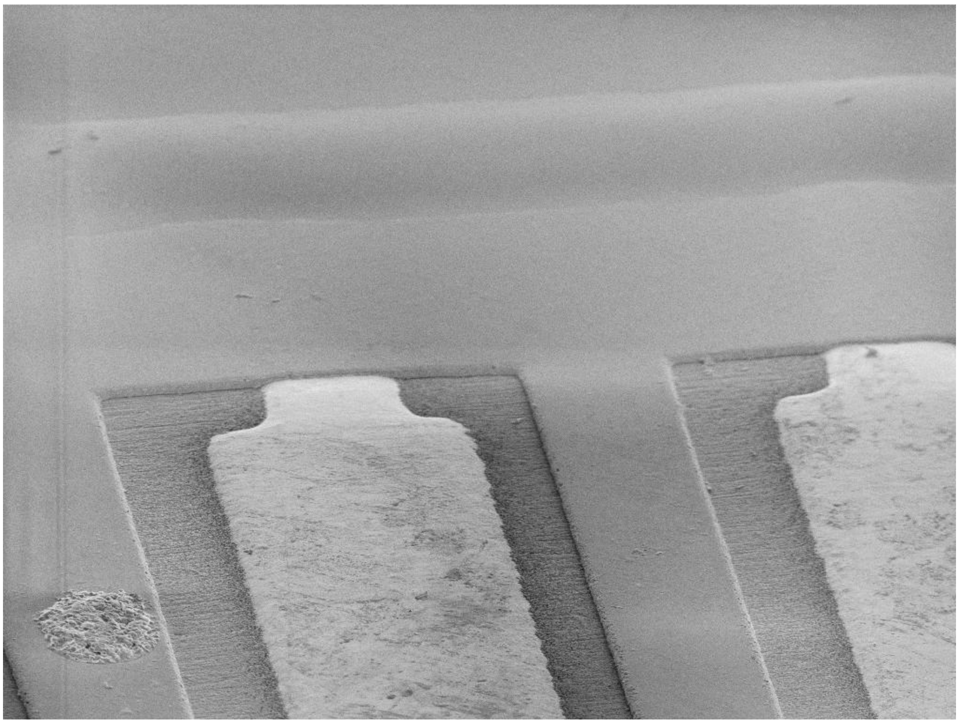

**Figure 7: SEM micrograph**

The final printed and solidified legend must show chemical resistance and adequate mechanical properties, (adhesion, hardness and abrasion resistance), to withstand further processing, aging etc. Processed legend features were tested[14] with the industry standard IPC-TM-650 tape adhesion test (method 2.4.1.1B) and chemical resistance tests (method 2.3.4B) on a variety of PCB substrates. All optimised feature specimens passed these tests.

# 6 System development

Engineering of the Jetmask DLP system has included the following elements of system development:

- System environment - to ensure a clean, dust-free environment, dry air is introduced under positive pressure.
- Work table – ergonomically designed clamping / vacuum system onto which panels can be directly loaded.
- Print head mounting – incorporating software driven print head height adjustment and easy removal for maintenance.
- X-Y addressable platform – Developed with Lavenir[15] and modelled on their photoplotter systems
- Alignment - A combination mechanical and optical alignment system that produces accurate registration of the printed image to the panel features. This includes full soft tooling with offset, data scaling and rotation to compensate for any panel distortion or hard tooling errors.
- Ink supply – including storage considerations relating to unintentional exposure to UV light and pumped delivery to the print head.
- UV lamp configuration – relating to optimum curing conditions.
- Software-driven electronics – for the variable hardware configurations relating to the process envelope.
- CAD/CAM data preparation - to allow rasterisation to be done in real time following any tooling manipulation, for insertion of dynamic text and serialization information, to produce uniquely identified panels and circuits within.
- System control software - for communications to software-driven hardware, as well as the operator interface and network compatible system control.
- Reliability issues – particularly relating to print head and UV-lamp lifetimes.

The outline technical specifications of the Jetmask DLP system are listed in Table 1.

# 7 Legend printing processes

## Silkscreen legend printing

Conventional silk-screen legend printing is the standard technique used for applying legend/notation/ident to PCBs, using either UV or thermal curing ink. The method involves CAD/CAM data preparation, phototool manufacture, screen film exposure, screen film development, stencil creation, stencil set-up, image print and image cure.

Photoimageable silk-screen legend printing is an alternative to the above method and produces far better results (feature definition/placement), but the wastage of ink is high (90%) and time to process is also increased due to the number or process steps and drying/curing times (thermal curing ink). This method is often used for smaller batches where a complete stencil set-up is too resource consuming. The process includes: CAD/CAM data preparation, photo-tool manufacture, stencil creation (blank stencil, no features),stencil set-up, screen ink flooding onto panel (total coverage), tack drying ink on panel, panel exposure, legend development and cure.

## Single-step Direct Legend Printing

By contrast, in the Jetmask DLP printing process, laminate panels are loaded directly onto the working table, the optical alignment system automatically registers panels to the accuracy needed as the table withdraws into the body of the machine where it undergoes print and cure cycles before the completed panel is returned - fully cured. The process only requires CAD/CAM data preparation, set-up and a print and cure sequence as outlined below:

- CAD/CAM data preparation – where the CAD is altered to compensate for design for manufacture (DFM), fiducial and inspection points, dynamic text entry and job queuing using a standard CAM or ‘JetCAM’ system.
- Initial product set-up - this is only really required for new jobs, not repeat product. The first-off product is placed on the machine bed, approximate fiducial positions, inspection points and printing height are set for production. These parameters are used as ‘base’ positions for each consecutive print of this job, including later batches unless re-configured. Critical measurements such as height are checked by the system before commencing print cycle. Dynamic data and panel information, such as number of panels produced and batch numbers, are saved to the product specific ‘job’ file, ready for the next time the job is run. Repeat jobs only require job file, panel thickness and alignment type selection, confirmation of product orientation and panel thickness, and dynamic text information input (if required).

The inherent advantages of the data-driven direct imaging single-step DLP process can be defined as follows:

- Process Efficiency. By imaging the legend from a software file, directly onto the board (ComSIT – Computer-to-Substrate Image Transfer process), DLP negates the need for photo-tooling, screen production or the need for a separate curing system as required for silkscreen production. The resulting drop-on-demand printing, only where necessary, greatly reduces the consumption of ink and eliminates the use of potentially hazardous photo-chemical waste. The instant set-up and processing results in faster turnaround and cost efficiency, particularly for short batch or prototype runs. For a single panel, the DLP process time is typically less than 5 mins., as opposed to over 1 hr for silkscreen printing. Other benefits include the space, labour and cost savings associated with a single, small footprint machine, a highly user-friendly interface via a Windows® based touch screen (Figure 8), and installation requiring only single phase power, a network connection and extraction.

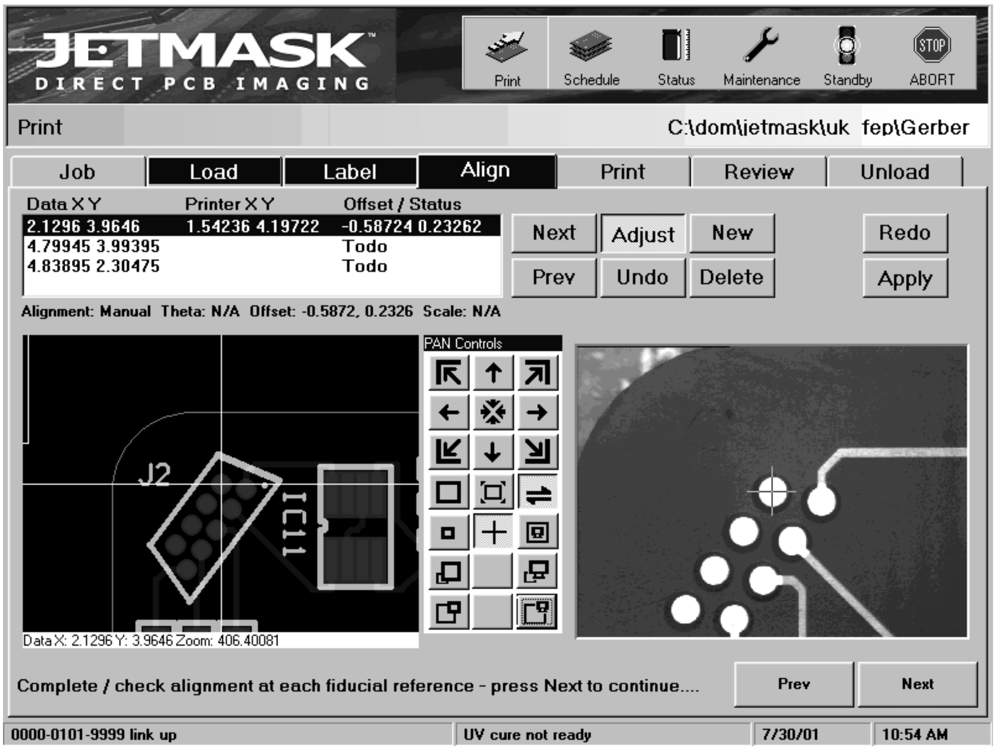


**Figure 8: Optical alignment via a Windows® based touch screen**

- Flexibility. Since DLP is data driven, no tooling is required and each image can be completely different. Dynamic data editing enables vast unique identification options, including serialisation, for panels and individual boards or circuits within a panel or batch.
- Quality. The capacity of the system to control not only the precise position and size of individual droplets of ink, but also their interaction with each other at the surface of the work-piece results in good legend definition even over 3-dimensional substrate features (Figure 5).

## 8 Future developments

Steps are already being taken to upgrade our legend printing systems taking account of advances in print head and UV-curing ink technologies. Throughput can be scaled by the addition of multiple inkjet modules and in the future automated panel handling will complete integration into process lines. Development work is also being undertaken to introduce DLP to further manufacturing applications such as direct printing of solder mask and direct imaging of etch mask layers for inner layer production. The inherent benefits in efficiency and flexibility can be transferred to these applications but for each application a number of issues need to be addressed prior to an operational system being developed.

For solder mask, in order to achieve the required solder coating of the exposed interconnection bond pads and surface mount component bonding lands, it is essential that the masking material be able to withstand the solder bath temperature and hot air levelling temperature relating to the solder type and thickness required for the application. For etch mask, issues include mechanical stability, chemical etch resistance, mask removal, etch feature definition and yield.

## 9 Conclusions

The use of piezoelectric drop-on-demand inkjet technology for legend and ident printing in PCB manufacture has been investigated. Development programs have been undertaken, focussed on key issues, such as the reliable and accurate placement of drops onto the substrate, control of the fluid interaction with the PCB surface in order to achieve good image definition, and consistent, fast UV curing of the materials. This work has led to the manufacture of an inherently clean and efficient single-step direct printing system to rival silkscreen legend printing. The advantages that single-step DLP affords over silkscreen printing include: process efficiency (faster turnaround, smaller footprint, reduced waste and cost), process flexibility (unique identification and serialization options) and surface independent print quality.

System development of piezoelectric drop-on-demand inkjet technology for other PCB manufacturing applications related to solder mask production and etch mask layers is being undertaken.

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