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Electronics Manufacturing by Inkjet Printing

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Abstract

Inkjet printing is of great interest in the field of electronics manufacture because its digital nature negates the need for physical tooling. A wide variety of active and passive materials are currently being investigated for use in inkjet printed electronics. These include semiconductors, light emitters and photovoltaic materials as well as dielectric materials and straight forward conductors. The range of conducting materials that can be printed is somewhat limited by the constraints of inkjet printing. Ideally, particle sizes should be below 1 micron and the viscosities and surface tensions of the fluids need to be tailored to the particular printhead being used. Regardless of these limitations, various technologies are now being implemented in the production of circuit boards, interconnects and antennas by inkjet printing. The properties of these inkjet printed circuits do not currently mimic traditional PCB materials – in particular, the sheet resistances of inkjet printed materials tend to be significantly higher than traditional copper clad laminate and the minimum feature sizes are somewhat larger than state of the art semi-additive plating. However, inkjet printed circuit technologies are a still finding many applications which are particularly well suited to their properties and the digital nature of their application.

Introduction

The digital nature of inkjet printing provides a very attractive proposition for the manufacture of electronics. The stage of board layout and prototyping has always proved a nerve wracking step in the product development cycle. Whereas the cost of each board in the final mass produced article may be relatively low, the initial prototype commissioned by the designer can prove significantly more costly. As well as the cost implications of errors in the design of prototype boards, the cycle times involved in the iterative loop often prove frustrating to both the designer and the project manager who is conscious of the pressures towards ever decreasing time to market. Therefore, the concept of a peripheral which would connect to a designer's computer and instantly convert the CAD data to a hard copy of the prototype board has long since been a highly desirable promise printed electronics.

Available Inkjet Printable Conductors

Printable conductors have been used for many years in the area of Polymer Thick Film printed circuits. In many cases analogue printing techniques such as screen printing, flexographic printing and roto-gravure printing have been used to deposit pastes of materials such as carbon or silver flake. Unfortunately, the rheological properties and particle sizes in these types of material are unsuitable for the majority of inkjet print systems. One of the first groups of conducting materials to be successfully deposited by inkjet printing were conducting polymers. Originally stemming from the work of Shirakawa, MacDiarmid and Heeger on the effect of doping polyacetylene with iodine vapour, many solution processable conducting polymers have been developed to be suitable for inkjet printing. Currently, the most widely used system is based on aqueous blends of polyethy(3.4-ethylenedioxythiophene) with polystyrene sulphonic acid. Often referred to as PEDOT:PSS, films of this materials system may be formed reliably inkjet printed with specialist printheads which are suited to aqueous conducting fluids and also the somewhat corrosive nature of the stock solutions. Although described as a conducting polymer, films of PEDOT:PSS used in printed electronics rarely achieve sheet resistances of less than 100 Ω/□.

The best performing Polymer Thick Film materials are typically variations of screen printed silver pastes. The success of these materials is partially due to the relatively high conductivity of the native oxide which forms on the flakes of silver metal used. The large size of the metal particles in the traditional screen printable pastes makes them unsuitable for deposition by inkjet. However, many companies have used advances in nano-dispersion technology to form stabilised solutions of silver particles with sub-micron diameters. Although many manufacturers of such inks claim solid loadings of greater than 50%, the relative density of the metal particles meant that the inks still have a very low loading of solids by volume. Because of this low volume loading of metal, multiple print passes are usually required in order to build up useful film thicknesses. Although the particle size in nano-silver inks is significantly below one micron, aggregation of particles can still result in reduced inkjet reliability. This is often the case in products with higher solid loading.

The as-printed films of nano-silver inks will typically have very high sheet resistances of tens or hundreds of Ω/□. Improved conductivities are usually achieved by sintering the films. Sintering at relatively low temperatures of 100^0C to 150^0C will cause a marked improvement in conductivity by driving off much of the remaining organic binder materials originally used to give the ink the appropriate rheological properties. In order to achieve optimum performance from the inks they must be sintered at temperatures in excess of 250^0C. The sub-micron nature of the particles leads to a depression of the melting point of the particles and allows the ink to partially fuse at temperatures which are significantly below the usual melting point of the metal. However, such temperatures are still unacceptably high for low cost substrate materials such as PET.

Another strategy to achieve inkjet printed conductors is to split the process into two distinct stages. By printing a catalytic material which is then rendered conductive in a separate plating stage, the requirements for reliable jetting can be separated from the properties required for good conductivity. Electroless plating is a process which has been widely used in the PCB industry, primarily for through-hole plating. Metal ions in aqueous solution are precipitated onto the surface of the substrate by catalytic reduction. The bath chemistries are designed such that the metal deposited is itself an efficient catalyst for the reduction reaction, thus allowing the plating to continue after the original catalyst has been covered. By formulating the catalytic materials into an inkjet ink, reliable patterning can be achieved without the concerns of trading off resulting film thickness with solids loading and inkjet reliability. Since the resulting conductivity can be determined by the length of time that the substrate is immersed in the plating bath, the thickness of the initial ink deposit becomes irrelevant to the conductivity of the final article.

Electroless plating baths have been produced with the ability to plate up to thicknesses of greater than 30 µm. However, at these thicknesses the mechanical properties of the deposited metal are relatively poor. Good quality ductile films of electroless copper are readily obtained with sheet resistances down to 30 mΩ/□, and this level of conductivity is found to be suitable for a wide range of applications.

Print and plate conductors also have the advantage that the metal surface produced may be easily soldered. Since it is similar to the metal surfaces found on traditional PCB boards other traditional post processes such as Electroless Nickel Immersion Gold (ENIG), immersion tin or silver, as well as anti-tarnish and Organic Solder Preservative (OSP) may also be applied.

The properties of the various inkjet printable conductors are summarised in Table 1.

Table 1 – Comparison of the Properties of Conductor Technologies

Substrate Material	High Temp	Yes	Yes	Yes	Yes
	Low Temp	Yes	No	Yes	Yes
	Porous	No	Yes	Yes	No
Solderability		No	Possibly	No	Yes
Waste		Low	Low	Low	Medium
Cost		Low	High	Low	Low

Properties of Inkjet Printing

Inkjet printers are now common place in both the office and the home. Desktop inkjet printers now produce ultra-high resolutions images in excess of 2400 dpi with picolitre drop volumes. Unfortunately, this type of inkjet printer can only be used for a very narrow range of fluid properties and in general, this level of performance can only be achieved on very specifically developed substrate materials. The industrial inkjet print heads that are commonly used in printed electronics generally have much lower native resolutions than their desktop cousins. Typically, industrial inkjet printheads will be built with between 50 and 360 nozzles per inch. The benefit of this type of printhead is the much wider range of fluids that may be printed. Industrial inkjet printheads are available to print a wide range of fluids with varying viscosities and surface tensions. In addition, many companies have developed inkjet printheads especially to withstand highly corrosive fluids or aggressive solvents that may be more prevalent in the field of materials deposition.

One class of materials which is commonly used in industrial inkjet printing is that of UV cure inks. By formulating an ink such that it will solidify under exposure to UV light, many advantages may be gained:

Drying times may be significantly reduced. Compared with the drying of solvent inks, UV curing can be virtually instant. This is particularly important in reel-to-reel applications where it is essential that the ink is dry before it is rewound.

Jetting reliability can be improved. Solvent based inks invariably increase in viscosity as the solvent evaporates from the ink on the faceplate of the inkjet printhead. Since UV inks tend to be non-volatile and rely on solidification rather than drying, the consistency of the rheological properties is maintained at the faceplate.

Image quality is improved. During the time taken to dry, solvent based inks may remain fluid and move of bleed on the substrate. By curing or partially curing UV inks immediately after printing, good image quality can be maintained.

By exploiting the wide variety of reactive species that are available in UV cure chemistry excellent substrate adhesion can be achieved. In many cases, UV inks can be designed to react with and cure into the surface of the substrate, leaving them covalently bonded to the material.

UV cure and solvent-based technologies may also be combined in a single ink to improve the compatibility of particular functional materials, while at the same time exploiting some of the advantages listed above.

Inkjet printing is a digital technique in many senses of the word. It is digital in that it allows the user to convert image data directly to physical output. It is also digital in that the features that are output are digitised: The widths of tracks and gaps increase in discrete steps or pixels. Figure 1 illustrates this with a photograph of some flip-chip bond pads on an RFID antenna. The four bond pads are separated by around 180 µm. This antenna has been printed at 360 dpi and the diagonal lines of narrowing lobes of the antenna clearly show the finite steps as the width of the line is reduced a pixel at a time.

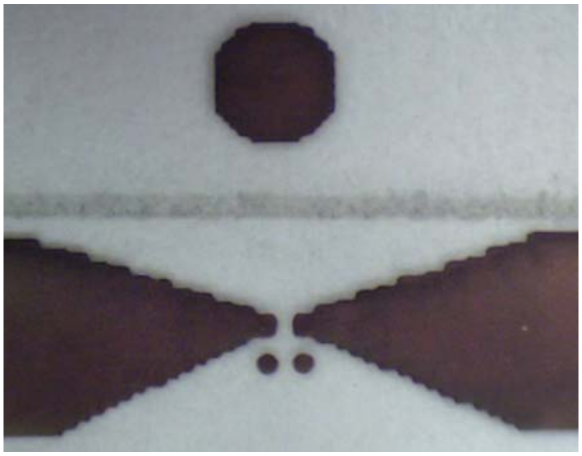

Figure 1 – Photograph of bond pads on UHF RFID antenna illustrating the stepped nature of diagonal edges

Although each pixel step at 360 dpi is around 70.5 µm, the narrowest track width is actually around 150 µm. The reason for this is shown in Figure2. If 70 µm discs are placed on the centres of a 70 µm grid then complete coverage is not achieved. The discs only touch each other at the vertical and horizontal edges and leave gaps along the diagonals.

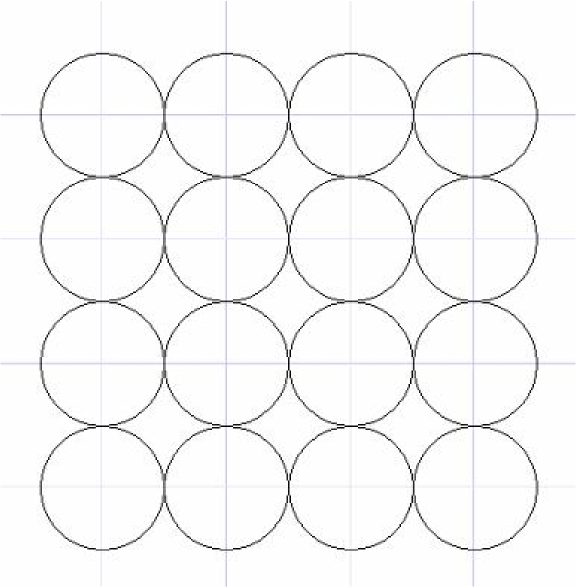

Figure 2 – Illustration of 70 µm discs on a 70 µm pitch

Figure 3 shows the ideal scenario of 101 µm discs on a 70 µm grid. This is the narrowest possible pixel size that will achieve complete coverage at this resolution. Figure 4 shows the more realistic case of 150 µm discs on a 70 µm grid. This situation ensures good coverage and also accounts for the alignment tolerance of the print system and other perturbations such as slight variations in the surface energy of the substrate.

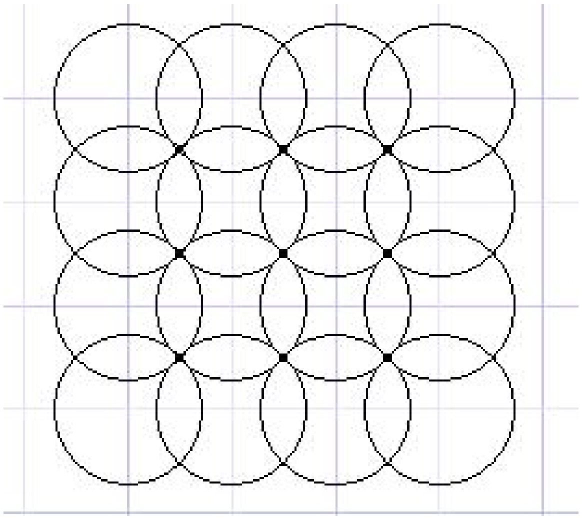

Figure 3 – Ideal case of 101 µm disks on 70 µm pitch

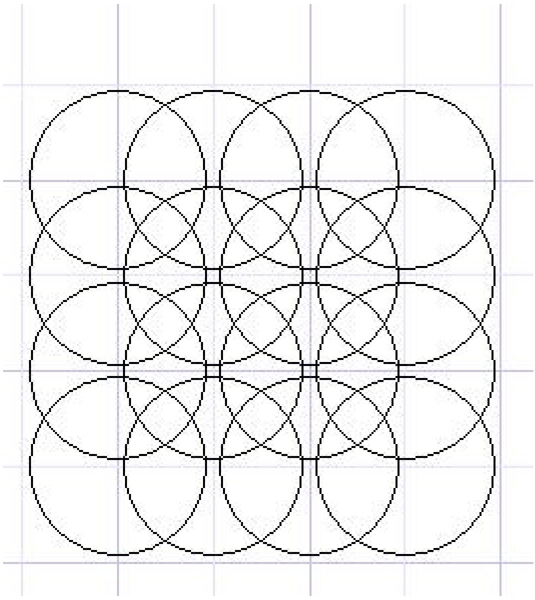

Figure 4 – Realistic case of 150 µm discs on 70 µm pitch

Many workers will report the demonstration of inkjet printed items with feature sizes down to 10 or 15 µm. Some are even using electrostatic acceleration techniques to produce sub-micron features with femptolitre drop volumes. However, these demonstrations currently only produce artefacts of a few millimetres across, at very low productions speeds in idealised laboratory conditions. The realistic minimum features sizes for readily available industrial production equipment are still limited to between 100 µm and 250 µm for single pass systems – with the possibility of around 50 µm features for multi-pass scanning systems.

The antenna in figure 1 was produced using binary inkjet printing. As the name suggests, binary images are produced from bitmaps where each pixel is either black or white – i.e. each position on the 70 µm grid either has a drop of ink on it or is left blank. The staircase patterns on the diagonal lines can be eased somewhat by the use of Greyscale technology. Greyscale printing still has the requisite that a grid position is either filled or empty but in this case, the size of the drop that fills the space may be varied across several discrete sizes. This is achieved by producing each drop of ink as the amalgamation of several smaller sub-drops. Whereas a typical binary industrial inkjet printhead designed to print at 360 dpi might have a drop volume of 40 pl, the greyscale equivalent would produce the same maximum drop size by firing 5 sub-drops of 8 pl in quick succession such that they join together before hitting the substrate.

This ability to vary the number of 'Drops Per Dot' allows the finite step sizes of binary inkjet printing to be reduced, thus giving the illusion of printing at much higher resolution. Figure 5 shows a plot of the width of single pixel lines printed at several different levels of grey. Each drop is made up of between 1 and 5 sub-drops, each of roughly 8 pl in volume. The trend-line shows a roughly parabolic fit to the scaling as would be expected by the volume of a disc scaling as the square of its radius. In reality the two limiting cases of the scaling would be molecularly thin discs with volume related to square of radius (the case for over wetting of the ink) or spheres of ink with volume proportional to the cube of the radius (the case for a completely de-wetted ink).

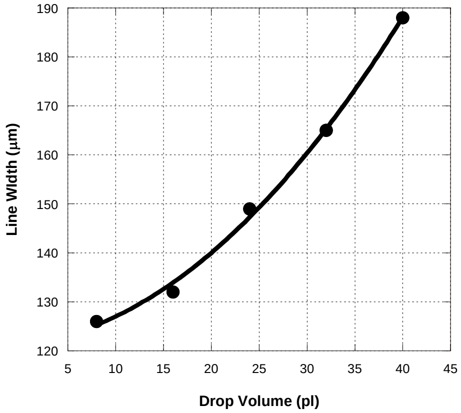

Figure 5 – Linewidth vs. Drop Volume for Greyscale Printing

Although the plot in figure 5 shows a roughly parabolic relationship between drop volume and line width, the achievable line widths still increase in discrete steps. However, in certain circumstances the surface tension of the ink may help to smooth out the edges of diagonal lines. Figure 6 shows an image printed with a greyscale printhead using five different drop sizes. The upper portion of the image shows the different finite line widths that are achievable. The lower portion of the image shows a 3 pixel wide gap between two thicker lines. In this case, the bulk of the lines are produced from grey level 3 which gives good coverage with roughly 150 µm dots on the 360 dpi grid. The inner edges of each gap have been produced by varying the innermost pixel from 0 drops per dot up to 5 drops per dot. Lines have been added to the centre image to clarify the boundaries. In this case the surface tension of the ink has smoothed the edges such that the finite steps between the different drop sizes can no longer be seen.

Greyscale printing is now widely exploited in the graphics industry where algorithms have been optimised to fool the human eye. However, software optimised for space filling and therefore the best reproduction of CAD data is still in its infancy and is not widely available.

Summary

Electronics manufacture by inkjet printing is now a reality with various technologies being available for production. Although carbon inks are unreliable and conducting polymers provide very poor conductivity, nano-particle silver inks and catalytic inks for print and plate conductors provide a viable production route with useful levels of conductivity and mechanical properties. In the case of print and plate conductors, their similarity to traditional PCB materials means that standard downstream processes like ENIG, immersion metals and OSP can be easily applied.

The wide variety of materials properties required for printed conductors rules out the use of desktop-type inkjet printers which have been optimised for aqueous inks in graphics applications. The industrial inkjet printheads which are more compatible with these materials properties tend to operate at lower resolution but do offer the advantages of wider materials compatibility and allow the exploitation of UV curable and solvent-based inks as well as the aqueous materials used in desktop technology. The use of UV curable ink technology offers many advantaged in speed of process, image quality and surface adhesion and is of particular use in reel-to-reel applications.

A significant difference between inkjet printed features and features produced by more traditional photolithographic means is the discrete features sizes obtained from the relatively low resolution of inkjet printing. Although this can appear as severe pixilation in binary inkjet images, the use of greyscale printing can significantly reduce this effect. In certain circumstances the effects of surface tension can be used to smooth edges out completely.

Current commercial Raster Image Processing (RIP) software is optimised for the graphics industry and while it will process greyscale images, the results are designed to best fool the eye rather than fill space most accurately. RIP software for materials deposition is currently under development and will provide the final key in the ability to fully exploit inkjet printing for the rapid and efficient production of electronics.