Micro-Electronic Printing: The State of the Art, Current Research Activities and the Future Potential.

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Abstract

The development of printable microelectronics is opening new markets for the skills resident in the printing community and the opportunity to add value to existing products such as packaging. This paper reviews the latest published research in what is a rapidly advancing science. The potential markets for printed flexible electronics are discussed, before examining the printing processes and materials that are being developed. Issues relating to the quality assurance are discussed as when printing a functional product, print integrity is essential.

The realisation of micro and nano technology is likely to rely on printing. In order to realise its full potential ther are still many areas, such as ink rheology where the impact on the process and the fundamental science is poorly understood.

Introduction

Graphic printing is a precision manufacturing process that enables the creation of microstructures, i.e. printing dots and lines in register to create an image. Micro manufacture by printing is the application of layers of grey "active" material in a pattern that produces a product on a flexible substrate. Thus, printing offers the most likely route of practically realising nano and micro technology. Thus, there is the opportunity to apply existing graphic arts skills/equipment to new products or for enhancement of existing products.

Major retailers are already stipulating that their suppliers will use Radio Frequency IDentification (RFID) technology from 2005 onwards. This is not just a security feature, but allows sophisticated stock control. This has direct

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benefits to the retailers as 75% of the cost of a product is getting there while stock outs cost 6% of sales (Das, 2003). It has the potential to enable the package to continuously monitor product quality. RFID may be passive or active, dependent on range and purpose.

Up to 100's of millions	30c to $100	Electronic
Up to 10's of billions	Up to 10 c	Small chips
Up to 100's of billions	Up to 1 c	Smart inks

Figure 1 : Cost / production volume of RFID tags.

Figure 1 depicts volume, cost and technology that may be used in tag manufacture. For example, conventional electronics may be used where tag costs are above about 30c, whereas smart inks are likely to be appropriate for very large volume manufacture where the target tag cost is less than 1c. To implement fully in retail, it will be essential that items at all levels of cost are tagged and therefore tag costs must also be minimised, tending in the long term towards the use of smart inks (with no interconnects) or smart inks combined with small chip technology (with interconnects) over the next ten years.

Micro electronic printing will enable truly "smart" packaging. The pill package that reminds you to take a pill and keeps a record of when you actually took the dose, so the physician can have a better assessment of the quality of the treatment. It is the ability to make point of sale advertising active and have a package where the moving display grabs your attention or plays a snippet of the DVD inside the pack. Already, there have been trials of a hair colouring package that has an in built timer that sounds an alarm when the colour should be washed from the hair.

The printing an alternative additive method for the manufacture of flexible electronics. Flexible electronics is an emerging technology that will have a substantial impact on many aspects of society. In communication, smart ink and substrate systems are already being used in the manufacture of products such as programmable remote controls for home entertainment. These use electroluminescent inks printed onto a thin flexible substrate as multiple layers comprising tracks and patches. Other applications include biosensors and an established example is blood sugar level detection. Figure 2 shows the typical dimensions of the printed component of an OFET that may be manufactured using polymer inks.

Significant markets are predicted in the western world for flexible electronic displays and medical bio sensor, that would justify the development on its own without even including the printed RFID, electronic devices, semiconductor and supplier industries.

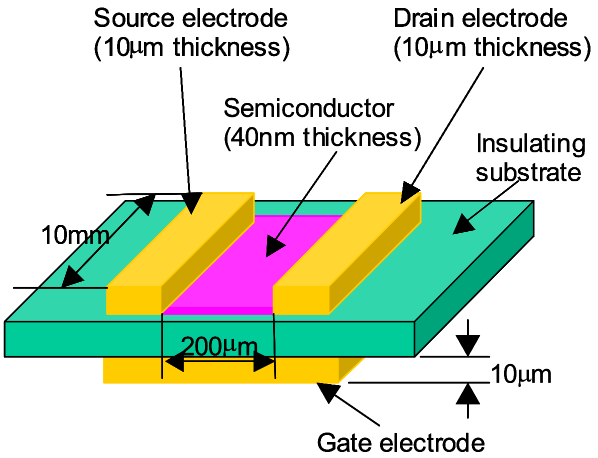


Figure 2: Dimensions of the Printed Components for an OFET

This paper describes the potential applications of printing for micro-manufacture, particularly the opportunities for printed electronics. The potential of the different printing technologies are reviewed, before discussing issues relating to quality assurance, inks and substrates characteristics.

Applications of micro manufacture by printing.

The most basic application of printing for the manufacture of flexible electronics, is the printing of conductive tracks. This can be used for flexible connections, cables or directly for heaters. The drive is to produce finer lines so enabling things such as the flexible needle sensors for inserting via hypodermic needles (Pittson, 2003). Direct printing of conductives is also used for the manufacture of aerials for RFID. Conventional such circuits were made by deposition, masking, patterning and etching. This is wasteful of expensive novel materials. Printing these means material is only applied where necessary. Much of the application is by screen printing as this provides a thick deposit, but is limited in terms of the width of lines and separations that can be a obtained. The target is for a 50μm track width and gap. Offset, Flexo and Gravure have also been used successfully to print conducting tracks.

High performance electronics has focused on the use of Silicon. Silicon has many advantages, principally the ability to manufacture very small feature sizes that coupled with the speed advantage of electron flow has the potential to create high speed computing. However, to achieve this requires photolithography, vacuum processing and high temperatures. This results in a high cost per unit area, but as each device requires only small area, resulting in a low cost per piece. It requires long production runs and is not appropriate for large areas. In recent years, the development of plastic electronics based on organic semiconductors and printable metals offers the potential for large areas, as there is a low cost per unit area, on flexible substrates. They are also transparent, so offer advances in photonics. The use of printing as the manufacturing process makes them suitable for short runs. However, the feature sizes have to be larger for them to function and this results in a lower processing speed. While there may never be a plastic electronic Pentium, there are already the world's first bistable reflective display, i.e. gyricon electronic paper, driven by an inkjet printed active matrix backplane and the first printed polymer TFT AM liquid crystal display (Mills, 2003).

While the use of plastic electronics can integrate into other applications, as can be seen in the previous examples, one of the main drivers for the development of printing for micro manufacture is light weight rugged (LWR) flexible electronic displays. LWR will create new market for electronic books and magazines, electronic school bags, toys and games. LWR displays are needed by the military (Freitag et al, 2003). There are a number of military applications for which the degree of flexibility and ruggedness varies. In battlefield centres there is a need to curve the display so that all the viewers can get an undistorted image when they are stood inside the viewing area. As this requires a fixed curve, then these have minimum requirements for flexibility and as they are transported by a vehicle only have to be moderately rugged, moderate weight and volume to offer practical advantages. However, other application such as a wearable fabric will require more flexibility, moderate rugged and minimum volume. For commanders in the field, a rollable battlefield maps would require maximum area in minimum volume while still being moderately rugged. The ultimate goal is a paper like replacement for the pocket map. For this it has to be light weight, maximum rugged to fit into a pocket. It has to stand repeated folding and unfolding. The advantage of LWR displays is when coupled with GPS and battlefield intelligence, the map can be up dated for the soldier on the move who will know precisely where they are. Ultimately they may move into camouflage, creating a large area image over for example a vehicle so it blends into the background. This level of sophistication is currently only available to James Bond to hide his Aston Martin in his last movie!

A major displays market is mobile phones (Kimmel, 2003). These require increasingly larger colour screens so they can effectively work as a mobile terminal. This increased functionality with more pixel and keys. There is a convergence of technology, already seen as the mobile phone combines camera, gps, MP3 player, FM radio, game engine.

OLED (organic light emitting diodes) are based on polymer electronics. A thin transparent layer of conducting material with a large work function such as Indium Tin Oxide is printed onto a transparent substrate (Figure 3). The transparent hole generating layer (PEDOT/PSS or PANI) is printed next. A thin (<100nm) of light emitting polymer is printed on top, with a final cathode layer. When 2 –5 volts is applied across the device then light is emitted through the front face. They offer many advantages over conventional LCD. These include low power consumption, thin form factor, lightweight, wide viewing angle, fast response, colour quality and brightness. However, they currently have a shorter lifetime. The device also needs to be encapsulated as exposure to the environment can cause rapid degradation.

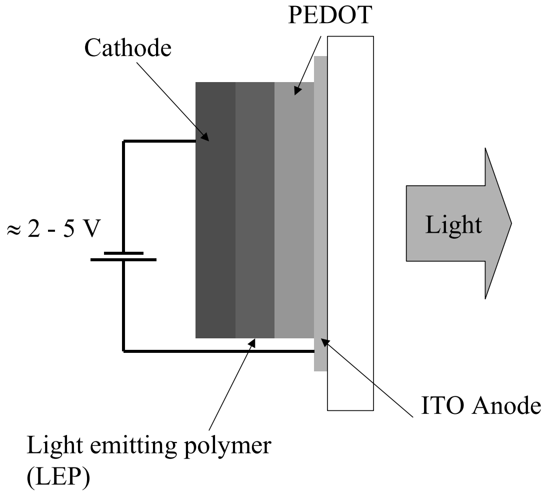


Figure 3 Schematic diagram of an organic light emitting diode (OLED)

This manufacture of this technology has focused on ink jets because of the need to achieve very thin layers. The absolute volume and control is essential for the display as drop volume variation produces a film thickness variation and results in a variation of luminance (Gregory, 2003). In order to produce a screen with very good colour gamut then it is essential that the colours are separate. This is achieved by creating a pattern of wells on the surface and accurately controlling the location of the ink jet head. Even once the material is in the wells, then care has to be taken to ensure the surface energies of the materials and the well are compatible, otherwise the materials can become non uniformly distributed and can even climb the wall into an adjacent cell. In the competition between the displays, resolution and size is key. In November 2003, CDT were displaying a fully functional RGB display with 75µm sub pixel pitch with 125x50µm pixel wells (Gregory, 2003). This means that the OLED display is approaching the small LCD displays current pixel densities of 648 RGB sub-pixels per inch (40µm sub pitch), with forecast resolution by 2004 >400 ppi (Williams, 2003).

As LCD displays require a glass like substrate, as displays get larger, the problems of handling the display during manufacture becomes enormous. For very large display pixel densities 5 ppi - 85 ppi are sufficient with single substrate or multi-unit tiled displays. This moves into the field of large flexible displays. While OLED and LCD have focused on achieving high resolution for small and medium applications. Electroluminescence offers the potential for coarser resolution at low cost per unit area (Fig.4). These comprise of a micro-encapsulated phosphor with a dielectric layer to provide insulation. There is a transparent front electrode, usually indium tin oxide (ITO) and a printed back electrode. An alternating current is applied to the electrodes which excites the phosphor. These have been used domestic hand held remote controllers for home entertainment systems, where the electroluminescence is used to selectively light up the display (Fryer, 2003). These are bright enough for day time viewing indoors with a limit of visibility 2Klux. They have an adequate life time 2000 hours without illumination. The high efficiency of electroluminescence offers the potential for battery powered products. Electroluminescence has also been used in point of sale displays (www.elumin8.co.uk). The ability to create dynamic displays is already being used in outdoor advertising, where large pixel size is not an issue. In fact, in some applications a single large pixel can be enough to create the desired effect. A single pulsating heart on the side of a London bus was used to advertise the file “Love actually”. This was driven from the buses own electrical system without excessive additional load. However, the brightness was only of such a level that it was effective at night. Similar hoardings have been use in transit areas with sophisticated effects.

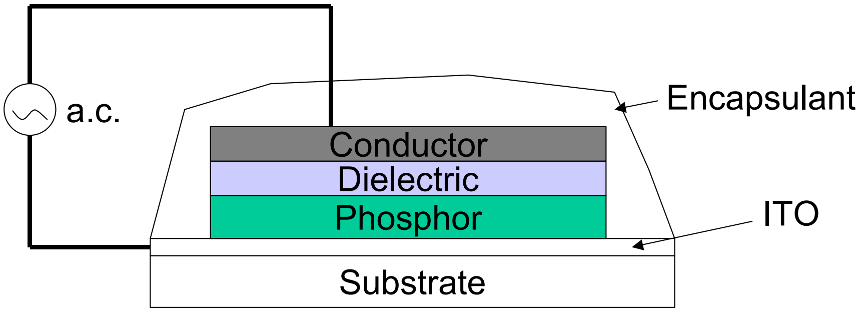


Figure 4. Schematic of Electroluminescent system

There is a shift in the advertising market as a result of social change (Goodwin, 2003). Households own more cars, with a higher number of women working than 10 years ago. Therefore, people are spending more time commuting, with less time spent at home watching TV. This is before one allows for the greater choice of channels that reduces the number of viewers per channel. Therefore, there is a shift towards out door advertising, i.e. at the roadside, on transport systems and at point of sale, as these are more effective at reaching the market. There are technical opportunities for new technologies to reduce the bill posting cost, enabling designs to be changed remotely. This offers the potential to change the advert to suit the customers. The outdoor advertising agencies are well aware of the footfall patterns in for example a mass transit system. It is only at certain times of the day that an advert will be reaching its target audience. Therefore, if it could be changed to match this pattern, not only could the agent get more posters on the same display, but the advertiser would get better value by matching their advert to the audience.

Thus, there are many significant markets for the manufacture of microelectronics by printing. The next section reviews the current use of printing for micro manufacture.

Printing Processes

Successful micro manufacture by printing requires intimate understanding of the printing process and impact of the processing environment, material performance and interfaces. At the design stage there is a need to understand the tradeoffs (e.g. channel length vs mobility), inter layer transfer and capacitance effects. The key issues that have to be resolved include:

- Resolution, both deposit thickness and feature size
- Degradation of materials when printed
- Registration on low cost flexible substrates
- Print topography

The process is complex since when multiple layers are printed, then the previously printed layers effectively form a contoured surface on which successive layers are printed. In graphics printing, this has a marked effect on colour reproduction [Hamblyn et al 2002].

Soft lithography also offers a potential route for printing electronics using a micro-contact printing (Drake, 2003). A mould is made into which are engraved the features to be reproduced (Fig. 5). These features can be nanometre size. A low viscosity resin is applied to the mould that conforms to these complex shapes to produce a pad. Raised nano- or micro-scale features formed on the flexible pad are then used to print the substrate. Materials that can be printed range from proteins, cells, metals, polymers to ceramics. Micro-fabrication of structures and device architectures has been demonstrated on a laboratory scale e.g. MOSFETs, TFT arrays, 3D microstructures for MEMS and optical components. Motorola, IBM, Phillips, Lucent have examined micro-contact printing processes on up to 15x15 sq-inch substrates. It has been found to be capable of reproducing line widths and multiple printed features to ±40nm, will the difference between the feature size on the pad and the print is ±40nm. Distortion, the variation in position relative to master can be as little as 1-2µm and registration 50-100µm. However, this is very sensitive to the printing environment particularly the mode of applying pressure to the pad. Thus, it is still likely to require several years to turn soft lithography into an industrial process.

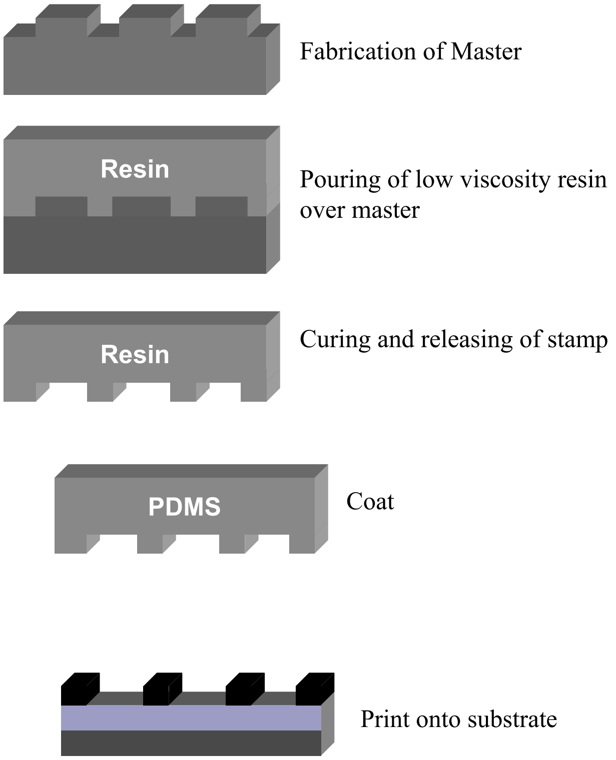
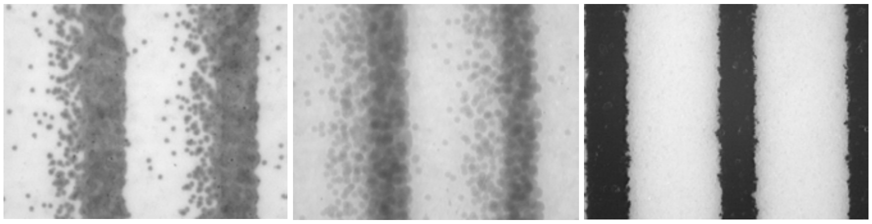


Figure 5 Schematic of soft lithography

Current research into printing of flexible electronics is focused principally on drop on demand ink jet technology [Yang et al, 2000]. Development has tended to focus on the head design to produce finer drop sizes at higher speeds. This restricts the materials that can be successfully fired through an ink jet without detriment to the performance. Ink jet heads prefer small, round molecules in the fluid with sub micron particles in a non-corrosive, non-volatile fluid of

25dyne/cm. Also, potential products need to tolerant of drop placement accuracy. Current industrial print head performance gives typical ±10μm placement accuracy and ±5% drop size with respect to nominal, but mechanical systems add to the positional errors. Ideally this will require development of new substrates that exhibit exceptional dimensional stability, or the localised and intelligent control of registration.

The satellite drops produced by ink jet can effect the functional properties of such a circuit. Hakola et al, 2003, highlighted this aspect in their study of the use of inkjet to print conducting polymers (Fig. 6). The formulation and viscosity of the black graphic ink produces a well defined line with no satellite drops. However, when an conducting polymer ink (PEDOT/PSS) printed with the same head technology, the change in viscosity creates small satellite drops that take longer to reach the paper. As a consequence produce a scatter of drops on the trailing edge of the line (the substrate is moving from left to right under the ink jet head), while the leading edge is better defined.



Coated paper (PEDOT/PSS)

Ink jet film (PEDOT/PSS)

Photo paper (black ink jet ink)

Figure 6. Comparison of ink jet printed lines 200μm wide (Hakola et al, 2003)

There is a need for well defined parallel lines. In order to ensure a continuous line despite the effect of satellite drops then several layers of ink have to be applied. The integrity of the line improves as measured by a drop in resistance (Fig. 7). However, economics requires rapid deposition and build rate. The speed is essentially limited by fluid properties.

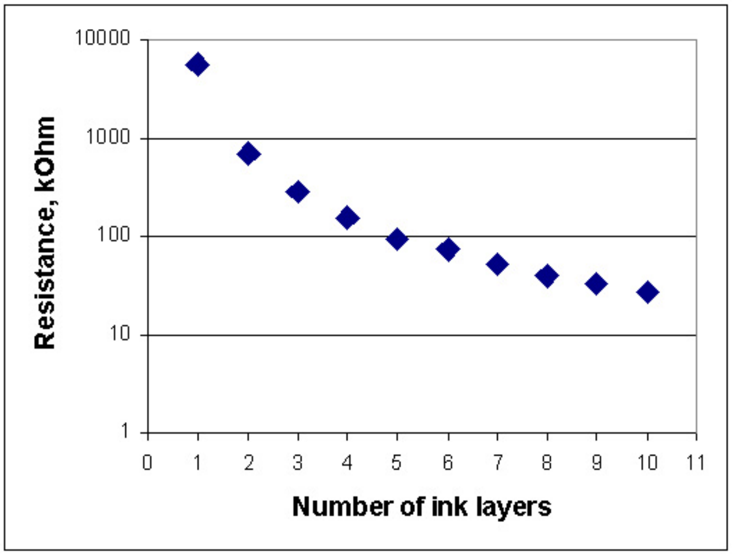


Figure 7 Effect of over printing on resistance (Hakola et al, 2003)

Despite their intensive development, the underlying physics of the formation of the droplet and its trajectory is not known . The drop is formed by the spherodization of a jet. Change in wetting at print head surface can dramatically change jetting properties. The ink rheology needs to be formulated to ensure a predictable droplet trajectory and to minimise the generation of secondary satellite drops that lead to defects. The shape of the deposit is controlled by the forces on the droplet. There is a trade off between jet velocity and sweep speed (Derby, 2003). The kinetic energy of the droplet is dissipated in extending the surface and viscous deposition. Low velocity produces a discontinuous line, i.e. individual drops at high sweep speed that first becomes continuous and then becomes progressively smoother as the sweep speed decreases. If the ink jet velocity is raised to compensate then splashing occurs at high sweep speeds but the line shape becomes distorted at low sweep speeds. Surface characteristics such as roughness and relative surface tension, can also effect the subsequent behaviour of drops on the substrates, e.g. when ink jet onto carbon epoxy substrate leakage along fibres can lead to an 80µm drop spreading to 200µm (Derby, 2003).

Ink jet print applies significant stress to the ink. In forming the jets themselves, the ink is subjected to a locally high shear stress while the ink droplets have to have a significant kinetic energy to reach the substrate accurately that is dissipated by splatting on impact and formation of secondary droplets (splashing). This may damage some of the materials that are required for micro-manufacture.

One of the main problems with this process is the printing speed that can be achieved is modest. Throughput can be increased through the use of multiple heads and increasing drop supply frequency. Increased life and reliability is required for the use in printing flexible electronics as any random nozzle-outs that occur could be disastrous for any fine features. This technology is likely to be most suited to high value products that will be manufactured in modest volume. Potential electronics industry applications are large area/low volume, e.g. electronic displays for outdoor and in-store advertising and flat screen TV. It may also find application in PCB manufacture.

In order to improve the resolution by limiting the effect of droplet flight variations and spreading on the surface, plastic logic precondition the substrate using image setting technology with the pattern they wish to produce (Mills, 2003). The polymer electronics are in water based inks. The area of the substrate where there is to be a polymer track is made hydrophilic, while the other areas are made hydrophobic. Thus, when the polymer is ink jet onto the surface, the ink jet controls the volume of the polymer delivered in approximately the desired area, but the final distribution is controlled by the surface energy of the substrate. Resolution of 5 μm can be achieved as standard and the potential for submicron resolution has been demonstrated. This process gives a high uniformity and high yield with accurate registration. It is the technology that has been used in some of the examples, e.g. the printed active matrix backplane described in the previous section. However, it is an inherently slow process, as the production rate is that of an image setter.

The technique that has so far had the most success in micro-manufacture is screen-printing. It is already used in biosensors and electroluminescent displays. This process is very adaptable and may be used to print virtually any ink onto any substrate giving a wide range of thickness. It has a major advantage in being intrinsically a low shear process thus can handle delicate particles in the ink and can be arranged to print quite coarse particles, although generally at the expense of resolution. Deposits from 5μm to 250μm are achievable. Screen-printing is the most consistent of all of the printing processes. However, the needs of precision manufacture to improve its resolution and control in film topography require a detailed understanding of the mechanisms of ink transfer during the process and the ink behaviour on the substrate before it has been cured (e.g. ink spreading due to surface tension and rheology effects).

There several interactions of the ink and the screen process that can effect the surface profile of the ink (Jewell et al, 2003b). For example large particles in the ink can lead to local voids, while mesh marking can be attributed to the interaction of the mesh with the ink as it is drawn from the surface. (Fig. 8). The surface of the ink can contract on drying. As the stencil pulls away from the substrate, the edges of the ink film can be pulled up. These all can interfere with subsequent printed layers, e,g. by locally reducing the capacitance of a dielectric or causing an uneven lay down of a subsequent track. These may also effect the performance of active materials, although sometimes with desirable results, such as increasing the surface area of a gas sensor and making it more responsive.

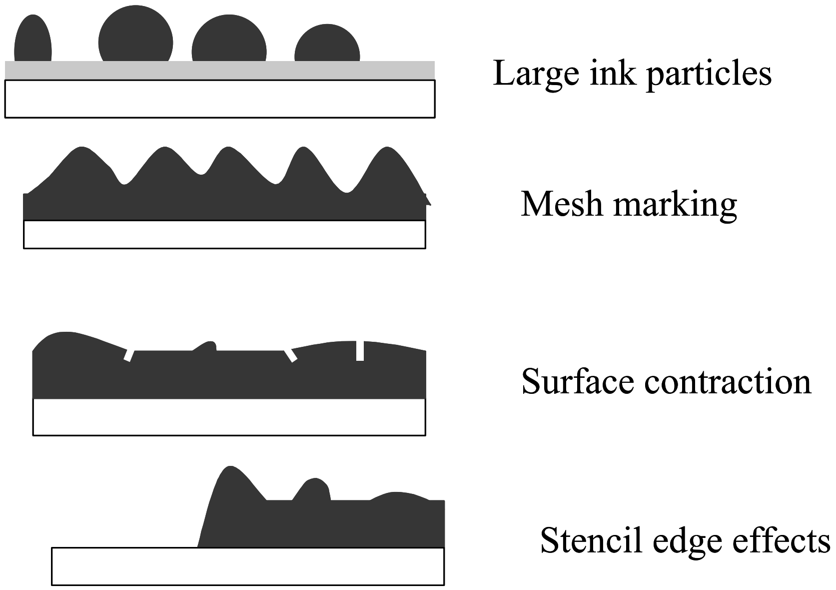


Figure 8 Generic screen printed ink film topology features

Offset Litho is also being considered for volume manufacture of flexible electronics. Transistors have already been produced that use offset in a multi-layer process with thin layers of active components applied by coating (Hubbler et al, 2003). Considerable attention had to be paid to the design of the device to achieve satisfactory electrical performance. An ink formulation that was adjusted in viscosity and surface tension to be similar to graphic offset ink was used to printing the source and drain. An ink film layer less the 500nm thick was obtained with gaps of <50μm and line widths <100μm. The quality of the gap on the plate is critical for printing narrow track and gap widths, the inherent roughness on the plate can limit the obtainable gap. This is further effected by the narrowing of the track width between lines as the ink film is squeezed during the offset printing process, identified by both (Hubbler et al, 2003) and (Claypole et al, 2004). This effect, which is seen as tone gain in graphics printing, means it is critical to establish the relationship between the image on the plate and the print.

An alternative process comprises printing a thin conducting layer of silver based ink by an offset process and building up the track thickness through electro-deposition to give a track having appropriate conducting properties [Lochum, 2002]. This process has a disadvantage since it requires two stages. Good track conductivity is claimed due to the homogeneity and density of the deposited metal. As this is still an additive process as copper is only deposited on the track, then it represents a material saving compared subtractive process where copper is applied and then selectively removed. It is claimed to achieve higher density via finer lines, a 20micron printed line typically plating to 30micron track & gap at 8 micron thickness (Sims, 2003).

There is also work on the potential to use flexography or rotogravure to print semi conductors (Makela, 2003). This has been shown to be feasible both on printability testers and on reel to reel presses (Fig. 9). 130µm line widths have been achieved with PANI ink (polymer semiconductor) and printing speeds of up to 100m/min have been possible.

Figure 9. Reel-to-reel printed conductive polymer structures gravure, Metso Pilot gravure (Makela, 2003)

Inks

The ink for systems for micro manufacture are inherently complex with a carrier, that can be a conductive polymer or confer additional properties as well as binding the particles and particulates whose shape and size is more a function of the application than considerations of the printing process. A critical factor in determining the ink transfer is the ink rheology, which must also consider the printing process and ultimately the product function. In order to maintain a low resistance conductive ink track inks must be heavily laden with a conductive solid particles (most commonly silver or carbon graphite) producing a high viscosity non Newtonian elastic visco-elastic material. There are further differences as the carbon inks that have large numbers of small particles of low specific gravity or silver where the particles are inherently larger, have a high specific gravity and can be in the form of plates. Thus, two inks notionally for producing a similar effect can have completely different rheometric characteristics. For thin ink layers, such as the semiconductor in Figure 2, an ink printed by the traditional print process will require dilution of the active low molecular mass component by between 90% and 99 % by a suitable solvent, forming a low viscosity liquid. The flow into and out of the image carrier recesses (mesh openings and roll engravings) will be dominated by fundamentally different forces in each viscosity range. Viscous and elastic force will dominate high viscosity ink transfer while surface tension, momentum and surface energy will dominate low viscosity transfer.

Printing characteristics and image quality are also affected significantly by rheology [Jewell et al, 2003a]. Under low viscosity conditions the dynamic spread of the ink placed on the surface will lead to increases in feature size as the liquid spreads over the higher energy substrate / previous ink film (a requirement of adhesion). Higher viscosity inks are less prone to slumping but may the correct release from the image carrier recess may required significantly higher forces. Also ink surface may be either smooth or rough, dependent on printing process settings [Jewell et al, 2003b]. Smooth surfaces are advantageous when multiple layers are over printed since this leads to a more consistent conductor cross section, whereas rough surfaces present a larger surface area and may possess advantages for sensor applications.

In order to successfully print active and conducting inks, research has focused on obtaining inks similar shear characteristics to traditional graphics inks. The viscosity of the ink can be changed by varying the composition of the ink (Fig. 10). However, these inks print differently as the relationship with constant shear rate only partially describes the fluid behaviour of complex inks. As well as flowing, such inks can exhibit elastic solid behaviour. Elastic solids release energy without loss when they return to rest, while viscosity causes energy loss when the substance flows.

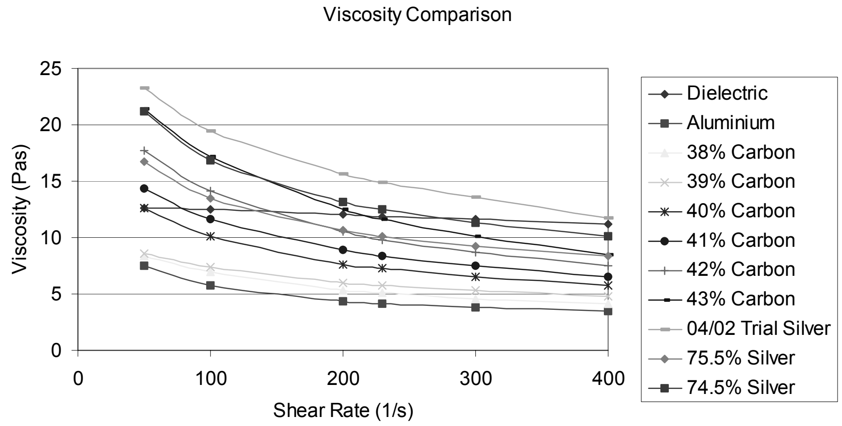
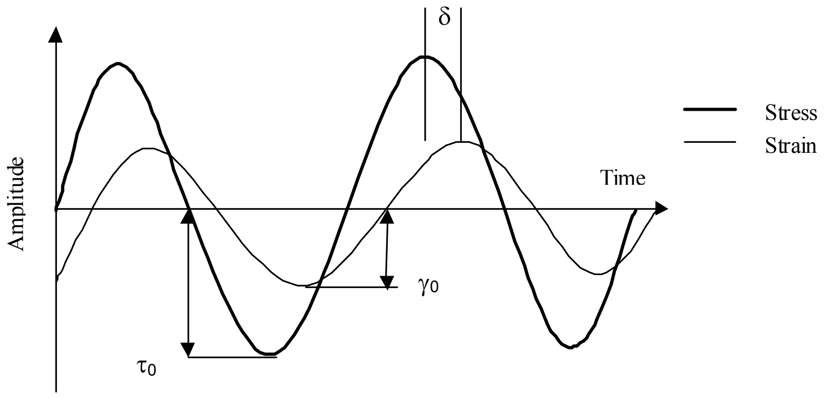


Figure 10. Viscosity versus constant shear rate for a conducting screen ink

In elastic systems the stress and strain are in phase, while viscous systems are 90 deg out of phase. Most real fluids are a mixture of the two and exhibit viscoelastic behaviour. As a strain is applied to the liquid, e.g. in a cone and plate viscometer, the induced stress lags behind by a finite time. This constitutes a phase lag when a cyclic strain is applied (Figure 11). This gives rise to a complex shear modulus that can be resolved into two components, G' (G prime) the storage modulus and G'' (G double prime) the loss modulus The ratio of G' to G'' gives indication of relative storage and loss.



$$\text{Complex Shear Modulus } G^* = \frac{\tau_0}{\gamma_0}$$

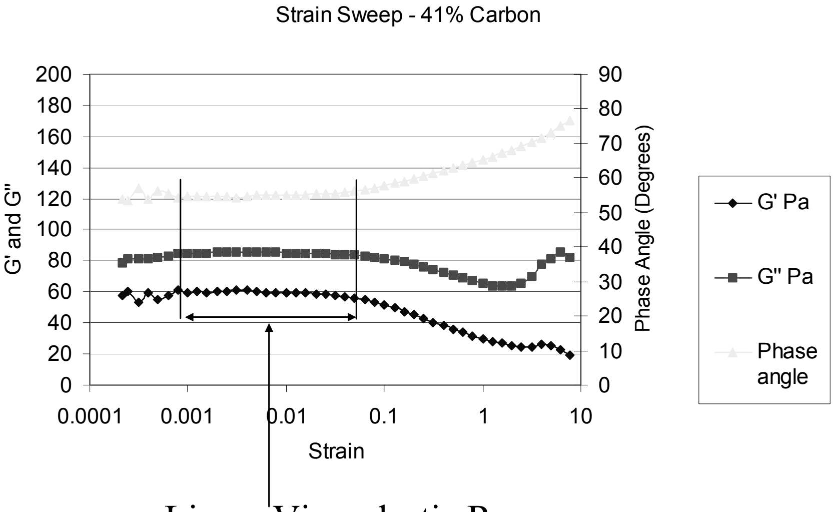
Figure 11. Relationship between stress and strain in a viscoelastic fluid subject to an oscillating strain.

One of the basic tests that can be performed is a strain sweep to determine the linear viscoelastic range. As a strain sweep is performed on a carbon conducting ink, a range of linear elastic behaviour is observed, while the aluminium conducting ink has no discernable linear viscoelastic range (Fig. 12). This difference in characteristic behaviour probably as the result of the interaction of the different particle geometry and shapes with the carrier fluid in the ink may be responsible for the difference in printing characteristics of these two inks which are of similar constant shear viscosity. There are other tests which can be applied such as frequency sweeps that mimic increasing shear and time sweeps that determines the "natural behaviour" of the samples over time. The relationship between these three measurement of visco elastic rheology with the underlying physics of the printing process has yet to be established. This is the subject of a fundamental research programme at WCPC.

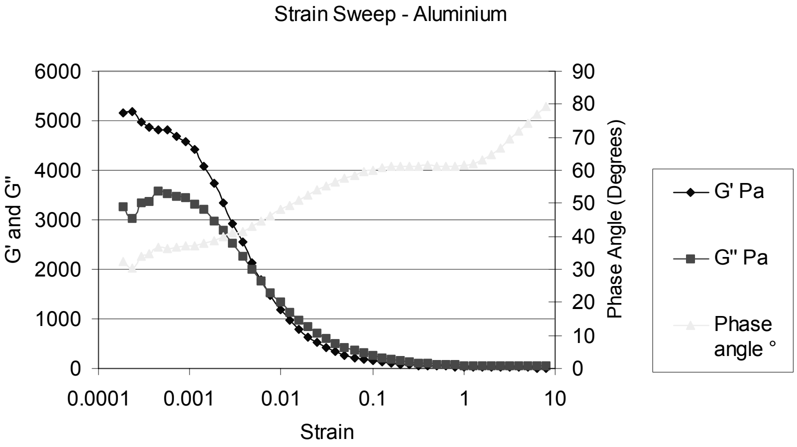
Surface energy is another key factor in achieving small feature size. The surface tension has an intrinsic effect on the ink release and transfer during the printing process. Once, on the substrate, the surface free energy controls the slumping and wetting of the ink before it is cured. This can have significant effects, as in conducting inks, where the carrier fluid can flow out carrying conducting particles into the beach area of the print.

Flexible Substrates

There are development projects to create thin layers of silicon thereby making it flexible (Drake, 2003). However, the main focus of recent research and development has focused on the tailoring the surface of polyester as an alternative to glass for LWR flexible electronic displays (Macdonald, 2003). This has been both in the mechanics of the manufacturing process and by the application of coatings. The coatings modify the surface properties offering specific functionality, e.g. organic adhesion, control the surface energy from 20-75 dynes/cm and can make the substrate hydrophilic/phobic. Other surface effects can be produced such as scratch resistance, solvent resistance and enhance barrier properties as required for encapsulation. Surface topography is critical for the manufacture of flexible displays. By both refining the manufacturing process and applying coatings, then compared to an industrial grade polyester that has numerous peaks over 50nm with some over 100 nm, an extremely smooth surface with no peaks over 50nm can be obtained (Fig. 13). This is ideal for OLED displays.

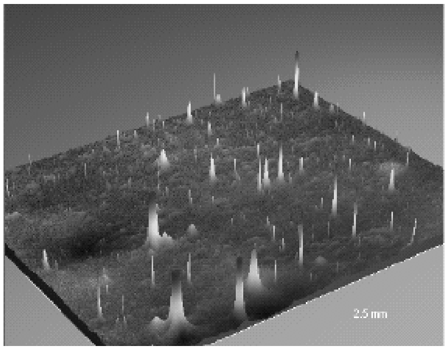


Linear Viscoelastic Range

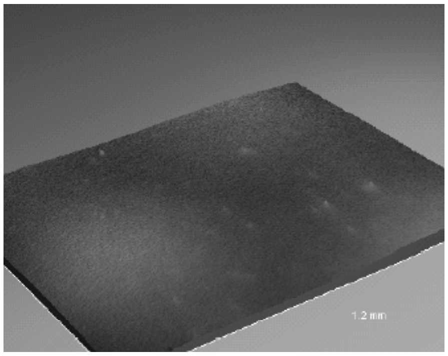


No detectable linear viscoelastic range

Figure 12. Strain sweeps of a carbon and aluminium conducting ink



Industrial grade - Ra, 2.55nm



Coated Teonex - Ra 2.27

Figure 13. Surface topography of industrial grade and display grade coated polyester film

For some applications, paper offers advantages in terms of recyclability and cost. However, it is inherently rough and has a tendency to absorb inks. To counter this the paper can be coated. The layer of fibres with associated porous structure can be seen in the lower half of the image (Figure 14). The coating is the more homogenious layer above. The silver ink appears as a layer on the surface. However, the offset printing process has forced the ink into the surface, the edge of the ink film being undetectable even with interferometry (Claypole et al, 2004). The resulting composite is not smooth but functions. The electrical behaviour of such composite active materials has yet to be established. There is also the problem of encapsulation, as paper is inherently porous. There is a need to develop compatible coatings that are impervious to oxygen, etc.

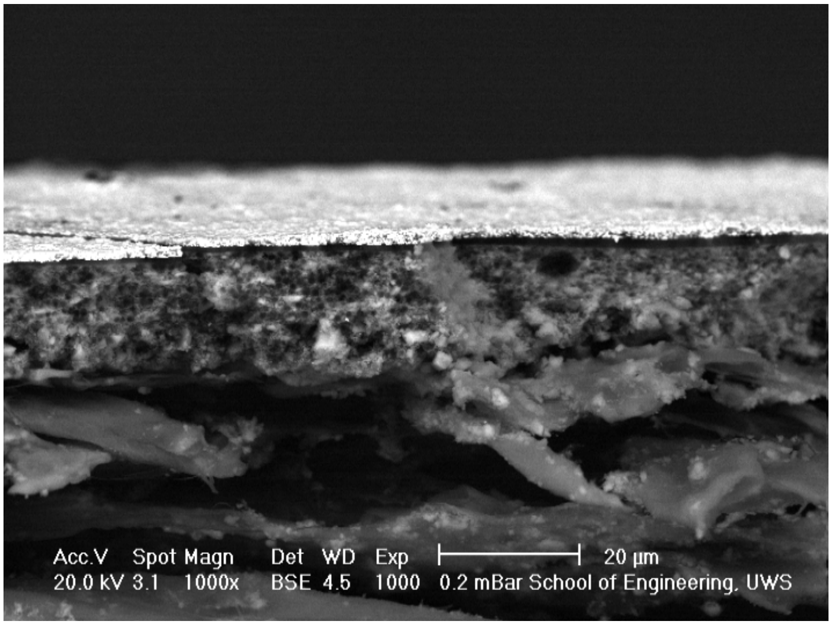


Figure 14 Silver ink offset printing onto coated paper

Quality Assurance

While the eye will integrate to compensate for small print defects e.g. breaks or holes in lines and ignore over spray drops, print integrity is essential for functional circuits. Performance determined by the cross sectional area and the surface finish. Performance of the printing processes for functional applications are expressed in terms of the track and gap, i.e. the smallest feature size that can be consistently obtained.

Image Analysis offers many advantages for quality assurance as it fast and thus offers on line potential, but it produces only 2 dimensional information. There not only has to be continuity, but consistent cross sectional area or else properties such as resistance and response will be effected. There must also be no tracking, i.e. printing in the non image area. There is a big thrust to obtain information from image analysis that can be related to the functional properties. In ink jet, it has proved possible to relate the image density and holes directly to resistance (Hakola et al, 2003). Other work on screen printing (Jewell et al, 2003a) has focused on edge characterisation, using statistical and frequency techniques with process knowledge to establish relationships between the 2 dimensional images and the 3 dimensional structure. For example, in screen printing "mesh marking" results in a line that varies in phase in both height and width (Figure 15). Thus, an algorithm can be established that relates the height with width at any point and hence the cross sectional area of the line. However, if the edge of the line shows random rippling, then the height is a function of the printing parameters and the cross section calculated directly from the width.

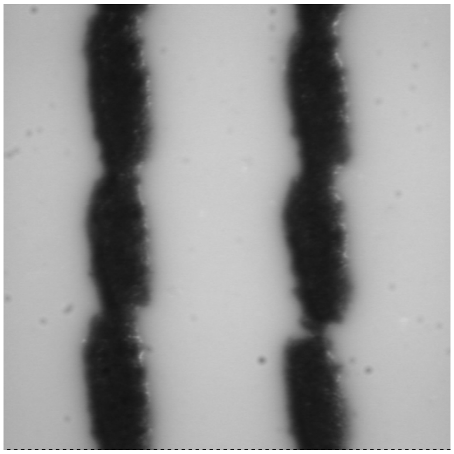
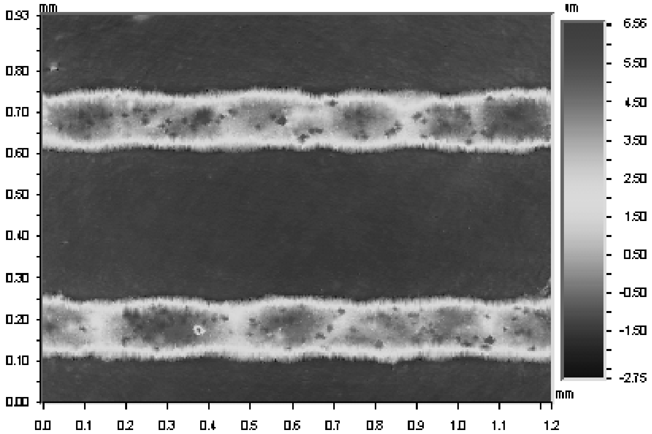


Image processing



Inteferometry
Figure15 Mesh marking as seen by image processing and inteferometry.

Closure

Micro-manufacture by printing is a disruptive technology that will revolutionise the manufacture of existing products and enable new products. It is an opportunity for the graphic arts industry to move into the manufacture of higher added value products. However, to achieve this there is a need to consistently achieve small feature sizes with quality control appropriate to the electronics industry. This will require the development of processes and materials, the key to which is a scientific understanding of the process physics. Even with the current technology, it is on the verge of producing viable products. Beyond electronics there is a whole raft of exciting possibilities where printed is the most likely method of volume manufacture of micro-technology, such as sensors, bio-medical applications and live cultures.

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