Paper substrates for device manufacture – a technical roadmap

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Abstract

Paper is the chosen substrate for much of the output of commercial printing. Printing methods that were developed for and matured in commercial printing are now being applied to electronic device manufacture in applications areas such as printed electronics, printed displays and photovoltaic devices.

One of the key strengths of paper as a substrate for printed devices is its widespread acceptance for many existing applications. This paper examines the technical issues involved in moving paper substrates into printed device manufacture. The work shows the key technical areas that need to be addressed. The work begins by contrasting the characteristics of paper with that of an "ideal" substrate. It then proceeds to describe options to modify paper to address these. It examines the options for paper coatings and barrier layers that can be applied both at substrate and device manufacture. It also examines the issues around printing fluids and methods from the perspective of fluid/substrate interactions. Finally it sketches out a road map for taking paper substrates from "lab to fab" in device manufacture.

Introduction

The use of paper as the substrate in printing processes can be considered to be a mature technology. However, there are now new applications being developed that, while using the existing technologies require substantial modifications to make them a realistic option in the market place. One of these is printed electronics, the ability to print electronic components and complete devices onto substrates.

Printed devices are now beginning to appear and paper would appear to have a place in this new technology, due to the widespread acceptance of paper substrates for many existing applications. The future may well lie in mixed documents, containing both conventional print and printed electronics.

In order to optimise paper based products for these applications the physical and printing characteristics must be re-examined and some modifications made in order to make them suitable. This paper looks at these under three headings and these provide the framework for the roadmap. These are as follows:-

1. Printing "fluids" and the choice of printing press.
2. Surface modification of paper
3. Barrier layer technology.

However, in order to understand the issues involved it is necessary to look at the reasons why paper substrates have a place in this emerging market.

Why use paper substrates?

This is a useful question to ask as it will guide us on the content of the roadmap. It should also be noted that this work does not attempt to make the case that paper is in any way "better" than other substrates. It is however suggested that paper substrates have a significant place in the future of device fabrication.

At this present time when it comes to substrate choice there is a difference between technological capability and potential market volumes, as illustrated in Figure 1.

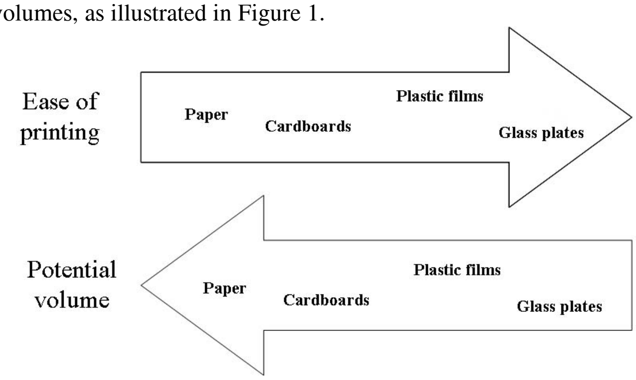

Figure 1 The disconnect between technology and market potential

If substrate choice was left entirely to the person doing the printing, glass plates would probably be the choice. The flatness, rigidity and inertness of glass make this a comparatively easy product to work with. [1] As a result a number of early printed fabrication demonstrations have been conducted on glass substrates. For roll to roll capability plastic films have a number of the desirable qualities of glass but provide a route to flexible devices without fragility.

The introduction of cardboards and papers produce many more problems. In addition to the fibrous and non-uniform nature as illustrated in Figure 2 there are problems with dust, debris, porosity and a host of other issues. From the sole point of view of the practicalities of device fabrication, these materials have little to offer.

However, from an applications point of view the emphasis is in the other direction. Paper and cardboard are still ubiquitous materials in the world around us and are much in demand in applications such as toys, novelties and packaging. The integration with conventional print onto traditional substrates provides a strong incentive for value added in a number of applications. Even so, there are many who still argue against the utility of paper in this field.

One argument looks specifically at performance. The surface roughness of paper is inherently larger than some of the synthetic substrates. This has 2 potential implications.

1. As a result paper cannot achieve the sort of feature sizes that plastic substrates are capable of. While this may well be true it neglects the fact that there are simple applications such as novelties and toys where feature size is unlikely to be an issue. Indeed, larger features have the advantage of fault tolerance, a particular issue in security and high value packaging applications.

2. Printed metallic conductors will have lower conductivity. Again this may well be true unless thick films are deposited using methods such as screen printing. However, once again there are applications which will circumvent this. For example toys and novelty applications may well avoid silver conductors as they have undesirable biocide properties when the item may be chewed by a small child.

For smart packaging and other applications paper is seen as potentially useful. Printing on paper is very logical and it would seem to be essential to the emergence of a significant smart packaging sector. Coated papers are already in use for printed antennae for RFID devices. [2] By 2013, it is forecast that paper substrates for printable electronics will reach $0.5 billion in annual sales. [3]

Printing "fluids" and presses

Virtually every traditional printing mode (screen printing, flexographic, gravure, offset) has been or is currently being used for creating devices of some kind. [4] This mix of printing technologies looks set to continue as each has specific attributes to offer for device manufacture. [2] Conventional printing systems such as flexographic, offset and gravure are best suited to mass production and this will likely continue in future applications. Screen printing also has a place and some early commercial electronics printing activity such as the creation of RFID and novelties is being done in this way. More complex devices are likely to be fabricated using a mix of these techniques, depending on the desired characteristics of the individual layers. In addition to the choice being determined by the normal parameters such as run length and variable data requirements we must now add resolution, design rules, accuracy, interlayer registration and device yield to this list. The effect of some of these variables on device manufacture has yet to be assessed. [5]

However, in order to progress this further work has to be done on the "fluids" for these printing systems. While there is extensive work going on in terms of inkjet fluid development, seen at this and previous Digital Fabrication conferences, the literature on toner based systems is rather less extensive. [6,7]

The formulation of printing "fluids" for the various presses is the first element in the roadmap. However, we should not look at this in isolation as the fluid and the printing substrate must be considered as a system in order to get suitable device performance with as few practical restraints as possible. As a result we should consider modifying the surface of the paper substrate to best optimise the fluid / substrate interaction and thus optimise the device.

Surface modification of paper

Unlike many plastic materials under consideration for device manufacture uncoated papers have the problem that on the scale of the relevant feature size many papers used in printing are not isotropic. For example, plain paper and cast coated papers have significant surface features that can influence the form of the printed feature, as illustrated in Figure 2. [8] The effect of surface structure can readily be seen in the shapes of printed dots in inkjet prints on various paper types. [9]

Figure 2 Fibrous nature of paper. © MATAR Research Centre (Anna Fricker), horizontal field width = 1.25mm.

As a result all but the most basic of devices are likely to need some form of surface modification to the paper substrate. There are perhaps 3 options to consider for surface modification for the purposes of our roadmap. These are summarised in the following sub-sections.

Coating of the paper with a plastic layer such as a polyolefin.

This is established resin coating technology from the photo industry and has been shown to be efficacious for printed electronics. [10] However, as these systems are based on a thermoplastic they are not compatible with thermal sintering processes.

A plastic surface layer also has the advantage that in terms of wetting characteristics the paper then behaves rather like a plastic film. This has the advantage that fluids formulated for plastic substrates can then be used on such coated paper products. These plastic coatings also go some way to building barrier layer capability, covered later in this paper.

There are however a number of important disadvantages with this approach, all of which pertain to the fact that these layers would be applied at substrate manufacture. Many of the applications considered for paper substrates would require device fabrication over only a small percentage of the total paper area. The rest of this coating would go to waste, adding to the environmental impact and product cost. In addition one of the key benefits of paper, the ability to create hybrid documents containing both print and devices may well be lost as the plastic layer would constrain the number of printing technologies available for the printing step.

Coating of the paper with fluid receiving layers.

This type of technology is well established in inkjet media and also to some extent in electrophotography. [11] In some respects this technology looks to be a better option for compatibility with thermal sintering processes. At a previous Digital Fabrication conference samples of silver loaded inkjet fluids were shown during the exhibition printed onto standard porous inkjet paper. [12] Print quality was good but the product failed during sintering due to softening of the polyolefin layers and subsequent delamination and curl.

However, one particular disadvantage of porous layers for this application is their porosity. Fabrication using materials that are oxygen, pollution or moisture sensitive would be compromised by this porosity. Again the barrier layer technology described later would be needed to combat this issue.

It should also be noted here that the knowledge gained from the Image Permanence work on conventional printing will be of use in this issue. [9] Also, when it comes to the fabrication of biologically active devices and sensors the swellable polymer based technologies developed from photo products for early inkjet papers could also be useful. [1]

Image-wise application of a pre-coat.

This opens up a wide range of possibilities and may lead us into hybrid printing applications. By this technique the surface would be modified only in the areas requiring device printing. This pre-coat would be applied by a printing process in the same sort of manner as that described for barrier layers later in this paper.

Finally, there is the issue of de-inking for recycling to consider. As we move towards printing devices for applications such as packaging the potential environmental and recycling issues need to be addressed. These are already a cause for concern in conventional digital printing and printing devices is likely to add another dimension to this. [13]

Controlling the morphology of the printed dots is key to making paper substrates work for printed devices. The paper surface modification and the fluid design must be considered as a system in order to optimise the fluid / surface interactions. However, at the moment the emphasis does not appears to be in this direction. For example, from the perspective of the head manufacturer the issues are around compatibility of the printing fluid and the inkjet head. [14] Similar perspectives are taken by fluid manufacturers. This could turn out to be an impediment to adoption of paper into this area. Although there is some basic work on ink / media interactions published [15] the area does not seem to have the attention that this area warrants. [1]

The issue of fluid / substrate interaction is likely to be even more complex when it comes to the fabrication of sensors and biologically active devices. It has already been demonstrated that paper substrate type is a key variable in the printing of bio-analysis devices. [16]

Barrier layers

One of the issues still to be dealt with for paper is the provision of suitable barrier layers. Barrier layers are impermeable layers designed to seal sensitive areas from the effects of moisture, air or pollutants and can be applied above and below a sensitive area. In this case the barrier would be in the form of a “sandwich” with the printed device in between the layers. In common with lamination technologies used in conventional print there would be a requirement to seal the edges of the device too, to prevent ingress at these edges.

Paper as a substrate is porous to gas and moisture exchange and in the uncoated form has significant surface structure, as illustrated in Figure 2. This is likely to be a problem with some materials envisaged for printed devices.

While the surface structure is likely to be dealt with by the surface modifications covered in the previous section the porosity is more of a problem. It puts paper at a further disadvantage compared to the excellent properties of glass and the good properties of some plastic films.

So how much of a problem is this? It would certainly constrain the use of paper with highly sensitive materials such as those used in OLED manufacture. [17] However, this may be less of an impediment to the progress of paper substrates than would appear, for 2 reasons.

1. Early applications are likely to be using much simpler systems with less sensitive materials – see above.
2. There is already significant work in progress on barrier layer technology. This is being driven by the needs of the display industry for flexible yet robust displays manufactured by low cost roll-to-roll processing.

There is a caveat to this however. Some of the processes being envisaged for these barrier layers on plastic may not be well suited to paper substrates. Some such as plasma-enhanced chemical vapour deposition require temperatures and pressures that may render them unsuitable for paper substrates. In addition applications requiring mixed areas of conventional print and printed device may require the application and sealing of barrier layers over a local area after printing. In addition to reducing the expense of the barrier layer this allows a wider freedom for the technology used for the conventional printed areas as barrier layers may not take print anywhere nearly as well as coated or uncoated paper substrates.

The solution to this problem may therefore lie in printed multiple layers. Multiple layer barrier assemblies are presently being envisaged for OLED applications where layers are applied until the requisite barrier performance levels are achieved. There are a number of printing technologies that look to be suitable for the application of such barrier layers. UV cured layers in particular may find application here as may the less well known sealable layer systems. [18]

The development of suitable barrier layer technology is the third element in the proposed roadmap.

Conclusions

The use of paper and cardboard as a substrate for printed electronics has much to offer, particularly when integrated with conventional print. There are still technical issues to be addressed in terms of suitable printing fluids, coated media and barrier layers.

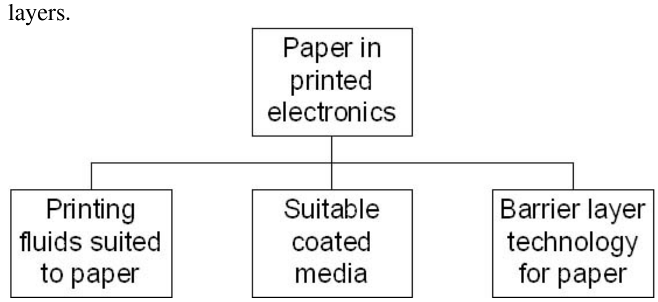

Figure 3 Roadmap to printed devices on paper substrates

Although Figure 3 and the body of this paper describes this roadmap in terms of 3 discrete elements this is for illustrative purposes only as there is much common technology between them. For example, the suitability of printing fluids will be governed by the type of coatings placed on the paper. These fluid receiving coatings may in turn be applied in the same manner as the barrier layers and may both be applied in the form of printing fluids.

So will it happen? Having studied this area my belief is that it will. There is certainly market demand and the technological hurdles do not appear to be any more difficult than those we faced in the transition to digital print. What remains to be seen is which groups and companies will rise to the challenge and reap the benefits.

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