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Summary

This summary of PRODI project deliverable D1.2 provides an overview of the work done in the Work Package one (WP1) to define roll-to-roll (R2R) manufacturing equipment requirements for three selected end applications in the field of printed and organic electronics.

The definition of roll-to-roll (R2R) manufacturing equipment requirements was focused on three end applications including: organic solar cells (OSCs), electrochromic displays (ECDs) and organic thin-film transistors (OTFTs). The selection of the three end applications was based on their high relevance for the printed and organic electronics industry and the need for removing their roll-to-roll manufacturing challenges. The selection was also influenced by the subject matter expertise of the consortium members leading the implementation of work in WP1. The consortium's approach was validated by the Industrial Advisory Board (IAB) of Prodi before actual implementation. The PRODI IAB comprises a group of leading printed and organic electronics companies from Europe.

The requirements definition work was performed by identifying critical customer attributes per application and creating specific linkages between customer attributes, application design parameters and manufacturing equipment requirements. The three devices and their manufacturing processes were analysed layer by layer. While doing so, the key technological challenges and solutions to these were identified. Also state-of-the-art technical parameters were specified for each process sequence in order to offer a baseline for the future-oriented target values also contained in the present WP1 D1.2 report.

The PRODI consortium's work in implementing the tasks of WP1 was supported by a Quality Function Deployment (QFD) method. It was used to identify critical customer attributes and create specific linkages between customer attributes and design parameters at application and manufacturing process level. A logical analysis approach also provided a well-organized structure for the present report. The results of the work done in the WP1 D1.2 were first presented in three stand-alone reports, which have now been consolidated into one integrated WP1 D1.2 report. The information contained herein is an outcome of an extensive literature review and the survey targeted at leading companies and R&D organisation in the field of printed and organic electronics in EU. This information has been further processed in internal and collaborative workshops by the members of the PRODI consortium. The responsibility of implementing the tasks was divided between the WP1 leaders as follows. Acreo of Sweden managed the preparation and implementation of the survey, VTT coordinated the workshops and managed the implementation of the QFD process and D1.2 reporting, TNO was instrumental in acquiring information through literature reviews and industry connections.

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1 Background & objectives

This section will describe the background and the objectives of the deliverable 1.2 Final requirements for roll-to-roll manufacturing equipment. The key objective here was to map out the requirements on roll-to-roll (R2R) manufacturing equipment from a process and application point of view.

In WP1, the consortiums initial work included making a questionnaire for distribution to the major European companies in the field of printed and organic electronics to gather the information on their current technologies and capabilities, as well as collecting necessary requirements in the specific format for the future development work. The target amount of companies was initially set at least 20, preferably 25. The target herein was, in particular, to obtain input on the applicability of different roll-to-roll manufacturing methods in manufacturing of selected printed and organic electronics end applications. However, very few questionnaires had been received as of the M12 review and the information provided in them was rather generic of its nature. The consortium made twofold conclusion. First, leading companies and R&D organisations in the field of printed and organic electronics were somewhat reluctant to disclose any detailed information on technological capabilities or requirements for roll-to-roll manufacturing equipment thereof. Second, the initial approach of defining roll-to-roll manufacturing equipment requirements for “printed and organic electronics” was considered to be too broad in terms of its scope and the outcomes thereof.

As a result the consortium decided to redefine its information acquisition strategy. The first decision was to narrow down the number of applications, of which, roll-to-roll manufacturing equipment requirements would be defined by the consortium. The selection of organic solar cells, electrochromic displays and organic thin-film transistors for analysis was decided in close dialogue between the PRODI consortium members and Industrial Advisory Board (IAB). The second decision was to focus on acquiring state-of-the-art information on roll-to-roll manufacturing equipment requirements through an extensive literature review. This approach was taken to acquire latest information available in public domain while the survey based information acquisition strategy suffered from a low response rate.

The results of the survey, the feedback from the IAB members and the state-of-the-art knowledge acquired from scientific publications – was used as a baseline for generating the requirements for the three individual end applications. Workshops were used as the primary method for this purpose. Three types of workshops were organised while creating the requirements. First, each of three WP1 leaders held internal workshops to form initial set of requirements for their selected application. Second, the consortium organised two meetings – one in Sweden, Stockholm, and one in Germany, Munchen – to refine the application requirements. Third, the IAB members and their experts were invited to the Munchen meeting to assess and give feedback on the set of requirements generated by the PRODI consortium. The Quality Function Deployment (QFD) method is widely adopted system specification tool that was used in WP1 to provide logic and structure to the requirements generation work implemented through workshops and input from specialists.

2 Overview roll-to-roll manufacturing methods

2.1 Printing

Printing is an additive deposition method that allows patterning, thus making it a suitable manufacturing method for printed electronics. [1,2] Printing also enables roll-to-roll (R2R) deposition on flexible substrates, thus increasing the manufacturing speed and throughput and decreasing the costs and amount of manufacturing steps. The main R2R printing methods are flexography, gravure, offset, rotary screen, and inkjet. The properties, advantages, and disadvantages of these methods are listed in Table 1 and 2.

Table 1 Advantages and disadvantages of different printing methods. [1-3]

Printing method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - Simple operation principle - Wide range of suitable substrates - Cheap, flexible, and soft printing plates → better contact - Low nip pressure → no damage to underlying layers - Easily adjusted and controlled ink amount 	<ul style="list-style-type: none"> - Poor print resolution and register - Low printing speed - Difficult to print solid tones and details via the same printing unit - Poor solvent resistance of the plates
Gravure	<ul style="list-style-type: none"> - Simple operation principle - High resolution, speed, and throughput - Excellent solvent resistance - Precise ink application 	<ul style="list-style-type: none"> - Expensive printing cylinders - Ink transfer problems → missing dots - Smooth and compressible substrate - Solvent recovery - Solid tones reproduced via ink spreading - High pressure
Offset	<ul style="list-style-type: none"> - High resolution and speed - Cheap printing plates - Versatile printing process - No excessive spreading - Waterless process possible 	<ul style="list-style-type: none"> - Ink-water balance - Water limits the choice of materials - High surface strength of the substrate - Rough ink layer - Complex process - High pressure
Screen printing	<ul style="list-style-type: none"> - Wide range of substrates and inks - Large amount of applications - Adjustable ink layer thickness - Low printing pressure 	<ul style="list-style-type: none"> - Low print quality and speed - Thick ink layers using pasty inks - Screen blocking
Inkjet	<ul style="list-style-type: none"> - High print quality - Non-contact method - No printing plates → direct imaging - No pressure - Curved substrates possible 	<ul style="list-style-type: none"> - Low speed - Resolution decreases with higher speed - Expensive materials - Nozzle clogging - Free spreading of ink - Surface tension of ink affects print quality

Table 2 Properties of different printing methods. [1-3]

Printing method	Printing speed (m/s)	Nip pressure (MPa)	Ink viscosity (Pa·s)	Layer thickness (µm)	Feature size (µm)	Registration (µm)
Flexography	3-10	0.1-0.5	0.01-0.5	0.04-8	40-80	20-200
Gravure	10-16	1.5-5	0.01-0.2	0.1-12	20-75	> 10
Offset	8-15	0.8-2	1-100	0.5-3	25-50	> 10
Screen printing	2	-	0.1-50	3-100	75-100	> 25
Inkjet	1-5	-	0.001-0.03	0.01-0.5, 20 (UV)	10-50	< 10

The operating principle of flexography is schematically shown in Figure 1. Flexography uses soft and flexible printing plates where the image elements are raised above the non-image elements, thus forming a relief pattern of the printed image. [3] Printing ink is applied onto the image elements via an anilox roller having small cells engraved evenly onto its surface. The surface of the anilox roller is flooded with ink from an ink chamber and excess ink is wiped off with a doctor blade so that ink remains only in the cells. Ink is then transferred onto the raised image elements of the plate and further onto the substrate in nips that induces the ink transfer by improving the contact between the ink and the plate/substrate. At the nip exit, the ink layer splits, thus transferring part of the ink onto the substrate.

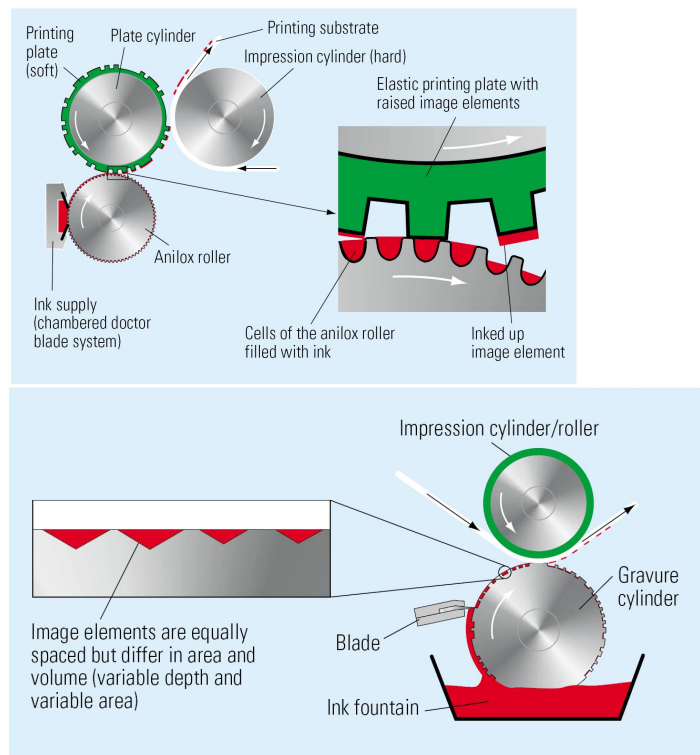


Figure 1. Operation principles of flexography (top) and gravure (bottom) [3].

Figure 1 illustrates the operating principle of gravure printing where the image elements are engraved into the surface of a metallic printing cylinder whereas the non-image elements remain at the original level. [3] To ensure uniform ink transfer, the image cells are always separated by cell walls even in the case of solid tones. Therefore, some spreading is required to produce solid tones. The engraved printing cylinder rotates in an ink fountain and picks up ink onto its surface. Excess ink is wiped off from the non-

image areas by a doctor blade so that ink remains only in the engraved cells. Ink in the cells is then transferred directly onto the substrate in a nip under pressure. The ink transfer is often improved by using an electrostatic assist (ESA) system which creates an electric field across the nip and lifts ink out of the cells into better contact with the substrate. However, this system cannot be used with metal or conductive inks.

Offset printing is an indirect printing method where ink is transferred from the printing plate onto the substrate via an intermediate blanket cylinder. [3] The image and non-image areas of the plate are on the same level but they have different surface energies: the image areas are ink-receptive and non-image areas ink-repellent but water-accepting. Dampening unit applies a thin film of dampening water onto the non-image areas after which the inking unit applies a thin layer of ink onto the image areas. The surface chemistry difference and the dampening water layer prevent ink from spreading onto the non-image areas. The inking and dampening units contain several rollers that carry ink/water via splitting to achieve thin, smooth, and uniform layers onto the plate. Some dampening water needs to be emulsified into the ink layer, thus the ink-water balance needs to be carefully controlled and adjusted. The ink layer is then transferred onto a conformable blanket cylinder and further onto the substrate in nips. The conformation of the blanket cylinder improves the ink transfer. The offset printing process is shown in Figure 2. Waterless offset does not use any dampening water but the printing plates are coated with an ink-repellent silicone layer which is removed from the image areas before the printing process.

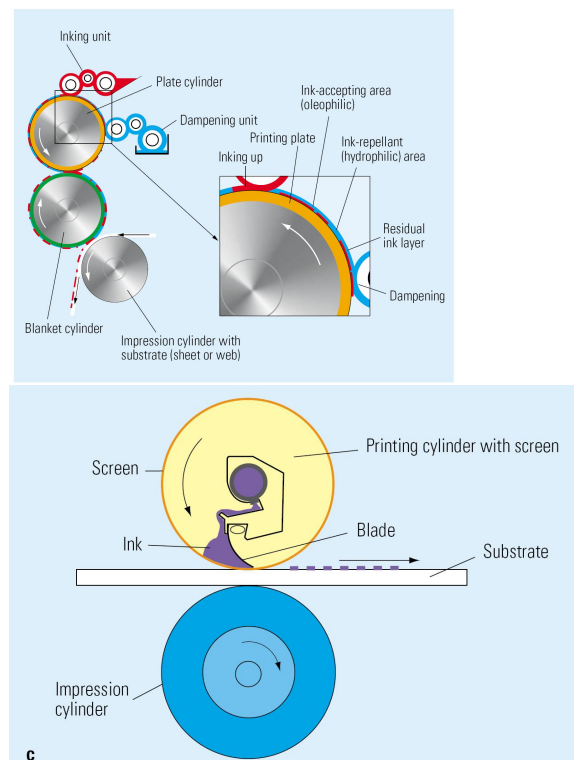


Figure 2. Operating principles of offset (left) and rotary screen (right) printing [3].

Rotary screen printing (Figure 2) is a push-through process where ink is pushed through a fine fabric screen made of plastic or metal threads. [3] The thread count should be large enough to pass through ink particles but fine enough to allow safe anchoring of the stencil. The non-image areas of the screen are covered with a photopolymer stencil that determines the printed image. The screen is flooded with ink which is pushed

through the image areas of the screen by means of a squeegee. The screen has a cylinder shape and the stationary squeegee and ink are located inside the cylinder. As the screen cylinder rotates, the squeegee forces ink out of the screen apertures onto the substrate.

Inkjet is a digital printing method where tiny liquid ink droplets are sprayed from nozzles directly onto the substrate according to the digital page data. [3] In continuous (CS) inkjet, a continuous stream of droplets is created by means of an oscillating piezoelectric crystal that pushes ink out of the ink chamber. The droplets are then charged according to the digital page data so that charged droplets are deflected, collected, and re-circulated and uncharged droplets strike the substrate. Due to the electrostatic deflection, metal inks cannot be used. In drop-on-demand (DOD) inkjet every droplet created strikes the substrate. Thermal inkjet uses local heating of the ink chamber as a result of which a bubble forcing ink out of the nozzle is created. In piezoelectric inkjet, a deforming piezoelectric element decreases the chamber volume and forces ink out of the nozzle. From the inkjet methods, piezoelectric inkjet has the greatest potential in printed electronics since the ink viscosity remains constant during the jetting, thus making the droplet formation and jetting more reliable and accurate and increasing the print quality and speed as well as the range of suitable materials. Operating principles of the different inkjet methods are shown in Figure 3.

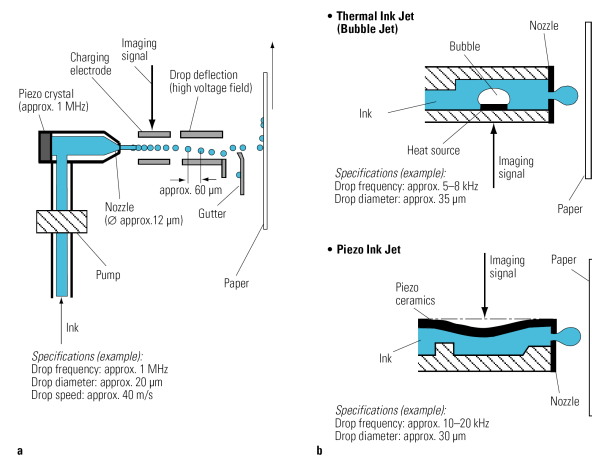


Figure 3. Inkjet printing processes [3].

2.2 Coating

Coating processes are able to deposit a uniform and smooth coating layer onto the surface of the substrate but patterning is typically not possible, which limits their usage in R2R manufacturing of organic solar cells (OSC). The coating process is divided into application and metering stages during which the properties and structure of the deposited layer are mainly determined. [4] The layer properties depend mainly on the rheology of the coating colour but they can also be controlled by changing the parameters of application and metering. The coating speed is typically 5-30 m/s and the viscosity 10-2000 mPa·s depending on the coating method.

In pre-metered coating techniques, a desired amount of coating colour is deposited onto the substrate and no metering is required. [4,5] The coating can be sprayed from nozzles, cast as a curtain or flown out of a coating head having a desired volume (slot-die). In slot-die coaters, coating colour is pumped into the coating colour chamber before application. The most common coating techniques require separate metering stage to adjust the amount of coating colour. Excess amount of coating is applied using

pond, roll, nozzle/jet or dipping application after which a blade/knife, air knife, roller or rod is used to wipe/blow off the excess.

Spray, curtain, and air-knife coating produce even and thin layers and they use lower viscosity coating colours. [4,5] Jet application increases the layer quality by eliminating layer splitting and splashing and enabling the deposition without contact pressure. This also enables higher solids content and decreases spreading. Blade coating can produce extremely smooth surface also on rough substrates but the layer thickness might be uneven.

2.3 Other roll-to-roll deposition and patterning methods

Other roll-to-roll deposition and patterning methods include evaporation, sputtering, embossing, and laser patterning. In evaporation and sputtering, a thin layer of material is deposited onto the surface of a substrate in vacuum. [6,7] Patterning is possible if masks or other subtractive treatments are used but these can make R2R processing impossible and increase the number of manufacturing stages and costs. In evaporation, solid material evaporates and condenses onto the substrate and in sputtering an electron beam detaches atoms that deposit onto the substrate. The maximum deposition speed is 0.1-10 m/s. Sputtering tends to be slower than evaporation and the sputtering energy can easily damage the substrate. Typically, metals are evaporated and conducting oxides sputtered.

Embossing and laser patterning allow R2R patterning but these methods require separate deposition stages where a uniform film is cast onto the substrate. [7-9] In embossing, a pattern is created by pressing a heated mould against it, and in laser patterning a laser beam removes material locally from a solid surface. Embossing is able to produce resolution of 30 nm-100 μm and laser patterning 10-50 μm . The processing speed ranges from some millimetres per second to 8 m/s. R2R laser patterning is often rather a slow process because the beam has to have relatively low energy to avoid damage to the substrate.

3 Organic solar cells

3.1 Abstract

Title PRODI WP1 organic solar cells manufacturing requirements

Technical Note ID VTT-PRODI-WP1-D1.2

Author(s) E. Jansson, P. Kopola

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Abstract:

This report describes the results of a literature and workshops carried out to generate and collect requirements on roll-to-roll (R2R) manufacturing equipment for organic solar cells (OSC). Based on the identified requirements, our task within the WP1 was to assess the applicability of different printing type manufacturing methods for producing organic solar cells. In doing so we first gathered information on the state of the art technical requirements for the fabrication of OSCs. This being done, we moved on to generating and defining future-oriented target requirements from same parameters and properties. Consequently, the present report provides state of the art and target requirements for the following OSC fabrication steps: substrate pre-treatments and converting, front side barrier deposition and curing, anode patterning and curing, hole injection layer patterning and curing, photoactive layer patterning and curing, cathode patterning and curing, contact pads and bus bars deposition and curing, and finally, adhesive printing and lamination. In case of each fabrication step, analytic discussion is provided to pinpoint the most fundamental problems, associated cause-and-effect relationships and potential solutions to overcome these identified technological challenges. As a conclusion, also the most potential production methods, including their advantages and disadvantages, per fabrication step are highlighted.

As the key conclusion of the work done we find that the most important and challenging layers that require significant development work include barrier and electrode layers. The barrier layers protect the OSC layers from oxygen and moisture extremely well, thus maximizing and maintaining the cell lifetime and efficiency. However, the barrier properties (WVTR, OTR) are still rather poor as a result of which further material, deposition method, and layer structure developments are required. In addition, the transparency requirement of the front side barrier layer limits the material choice and impairs the barrier properties. The barrier layer should be homogeneous since any cracks or pinholes create a path to moisture and oxygen into the OSC structure. An additional challenge arises from the fact that the substrate onto which the barrier layer is deposited should be clean and smooth so that defect-free and homogeneous barrier layer is obtained. The non-vacuum R2R deposition makes also the achievement of the barrier properties challenging. The electrodes should be highly conductive to obtain high lifetime and efficiency of the OSC. Therefore, the electrode layers should be smooth, homogeneous, and stable. Electrodes might also require inert atmosphere processing,

since they oxidise easily, thus diminishing conductivity. This places great demands for the R2R processing. The anode should also be transparent and have excellent resolution as well as sharp edges. The transparency and conductivity requirements require still material and process developments since highly conductive but non-transparent metals cannot be used. The cathode layer should be rather thick in order to protect the active layer from oxidation. Cathode inks are still under development since the lower work function of aluminium would be a more preferable choice than silver and commercial aluminium inks are not available. The final morphology of the cathode is determined in the sintering stage, thus making the sintering stage highly important. A thin electron transport layer might also be required under the cathode.

3.2 Organic solar cells technology overview

3.2.1 State of the art

Low cost organic photovoltaic (OPV) have been an object of intensive research during the last 10 years. Especially, due to its promise of low-cost manufacturing by high volume production methods such as printing and coating on flexible substrates, OPV has a powerful potential to become a novel optoelectronic device using as renewable energy source. Solution-processed solar cells are typically based on a conjugated polymer as a donor material blended with a soluble fullerene derivative as an acceptor material.

By spin-coating technique, the power conversion efficiencies of polymer-based bulk heterojunction (BHJ) solar cell, poly-3-hexylthiophene (P3HT) as a donor and phenyl-c61-butyric acid methyl ester (PCBM) as an acceptor, have reached up to 4-5 % under 1.5 AM (100 mW/cm^2) illumination [10,11]. The non-tandem based organic photovoltaic device with active layer consisting of an alternating co-polymer--poly[N-9"-hepta-decanyl-2,7-carbazole-alt-5,5-(4',7'-di-2-thienyl-2',1',3'benzothiadiazole) (PCDTBT) in bulk heterojunction composites with the fullerene derivative [6,6]-phenyl C70-butyric acid methyl ester (PC70BM) has lead to an improved power conversion efficiency 5.5 % [12]. In order to improve the efficiency further, stacking of low and high band gap materials into a tandem solar cell has been reported. Currently, the highest reported power conversion efficiency is 6.5 % [13]. 233 cm^2 module processed by spin coating having 1,1 % total area efficiency have been developed by Plextronics [14]. The disadvantage of spin-coating technology is the high material loss and incompatibility with high volume roll-to-roll processing.

It has been reported that several printing and coating methods are suitable for processing organic solar cells, including gravure printing, inkjet printing, screen printing, pad printing, doctor blading, slot die coating, spray coating etc. Ding et al. have obtained a power conversion efficiency of 1.68 % with organic solar cells containing rotogravure printed hole injection layer and active layer with an active area of 0.03 cm^2 [15]. There has been also development on inkjet side and increased efficiencies up to 3 % have been reported [16-18]. Krebs et al. have introduced pad printing as a technique for preparing the active layer [19]. Screen printing, knife-over-edge coating and slot-die coating have been combined in order to prepare an organic solar cell module with an active area of 75 cm^2 . [20] Giroto et al [21] and Hoth [22] et al have demonstrated the feasibility of spray coating to process organic solar cells. Power conversion efficiency ~ 3 % has been reached with spray coated active layer with an active area of 20 mm^2 . [21,22]. In addition, doctor blading [23] and screen printing [24] have been successfully used for preparing organic solar cells. Recently also an extensive review of OPV processing technologies have been published [5].

3.2.2 Applications

Organic solar cells are produced by utilising roll-to-roll manufacturing methods capable to mass production that is attractive solution from cost standpoint. Although the efficiency, device stability and lifetime do not reach the values obtained with inorganic based solar cells, there is market for organic solar cells. The main benefit of organic solar cells produced with roll-to-roll manufacturing methods is that it requires less capital investment in comparison to Si-based devices. [25]

In EC funded EURO-PSB project, flexible, a self-rechargeable polymer solar battery was developed. In addition, potential market applications have been evaluated which are summarised in Table 3. As it can be pointed out, the main parameters affecting the requirements for the solar cell module to be used in certain application are operational voltage and current, typical working duration per day/week, need for energy storage, conditions for light exposure including indoor/outdoor applications and requirements for the lifetime. [26]

Table 3 Potential end applications for organic solar cells. [26]

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Power range	Product description	Voltage	Running current	Typical use/day	Energy consumption/day	Storage needed	Conditions of light exposure
μW h/day	Basic calculator	1.4 V	10 μA	0.5 h	7 μW h	(NO)	Indoor/drawer
	Kitchen weighting scale	3 V	20 μA	10 min	10 μW h	NO	Indoor/cupboard
	Simple wrist-watch	1.5 V	0.4 μA	24 h	15 μW h	YES	Indoor/outdoor
	TV remote control	3 V	10 mA	1 min	500 μW h	YES	Indoor/drawer
	Alarm clock	1.5 V	Clock + ringing	24 h	800 μW h	YES	Indoor
mW h/day	PC keyboard (low power)	3 V	4 mA	1 h	12 mW h	YES	Indoor
	PC mouse (low power)	3 V	8 mA	2 h	48 mW h	YES	Indoor/under the hand!
	PDA	3 V	15-75 mA	20 min	15-75 mW h	YES	Indoor/pocket
	Small radio	1.2 V	15-150 mA	1 h	20-180 mW h	YES	Indoor/outdoor
	LEDs torch	3.6 V	20-100 mA	1 h	72-360 mW h	YES	Any
	Mobile phone	3.6 V	200 mA	0.5 h	360 mW h	YES	Indoor /pocket
W h/day	Mobile phone	3.6 V	200 mA	3 h	2160 mW h	YES	Indoor/pocket
	Laptop (personal computer)	12 V	3 A	1 h	36 W h	YES	Indoor
	Energy pack	3/6/12 V	Personal ultralight charger			YES	Outdoor

Possible applications for organic solar cells can be divided into four categories which have different requirements for the performance and lifetime:

- Category I: Low efficiency solar cells, short lifetime (1.5-3 years), mainly for indoor usage (consumer electronics)
- Category II: Low efficiency solar cells, longer lifetime than category I (3-5 years) outdoor usage
- Category III: Higher efficiency than with categories I and II, higher requirements for lifetime (5-10 years)
- Category IV: High efficiency, long lifetime (> 10 years), outdoor usage, organic solar cells for energy production in buildings (installed in the roofs of the buildings)

3.2.3 Component structure

Polymer solar cells compose typically of multilayer structure as shown in Figure 4. To simplify, an organic solar cell composes of following layers: substrate, anode, hole injection layer, active layer, cathode. Because the active materials are sensitive to moisture and oxygen, barrier materials should be deposited on both sides, front and back side, of the structure. Hole injection layer and active layer are sandwiched between

two electrodes, anode and cathode. Transparent conductive oxides (TCO) such as indium tin oxide (ITO) are typically used as anode material. Due to the limited conductivity of TCOs and the high price of the material, alternative layer materials have been investigated. One of the approaches is to use high conductivity PEDOT and metal grid layer to replace the TCO. The hole injection layer (HIL) smoothens the anode layer and enhance the OSC performance by creating a proper interfacial contact between the anode and photoactive layers, i.e., facilitating the charge transport. The most commonly used structure is bulk heterojunction device architecture in which the active layer consisted of blending two organic semiconductors having donor and acceptor properties in solution. In this deliverable, it is assumed that the cathode is prepared with roll-to-roll printing or coating methods. In order to improve the charge transport to the top electrode, possible interlayer will be prepared between the active layer and cathode layer. In addition, contact pads/lines will be prepared in order to get a contact to electrodes and connect OPV modules/component together. There are also more advanced structures; one of those is a tandem cell structure in which both high and low bandgap materials are stacked.

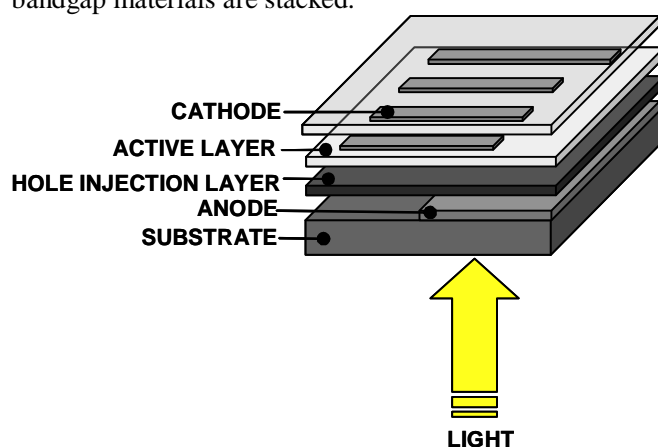


Figure 4. Structure of single OPV component.

Single organic solar cells produce output voltage at maximum ~ 0.5 V. However, in most of the applications, higher voltages is needed, so single organic solar cells need to be connected in series in order to produce higher output voltages. In series connection the anode of the first cell is connected to the cathode of the next cell as shown in Figure 5. The output current in directly proportional to the active area so in order to increase the produced electrical power the active area needs to be increased. Parallel connection can be used in order to improve the reliability of the solar cell module. If one single solar cell fails, the module still works if parallel connection is used in the design of solar cell module.

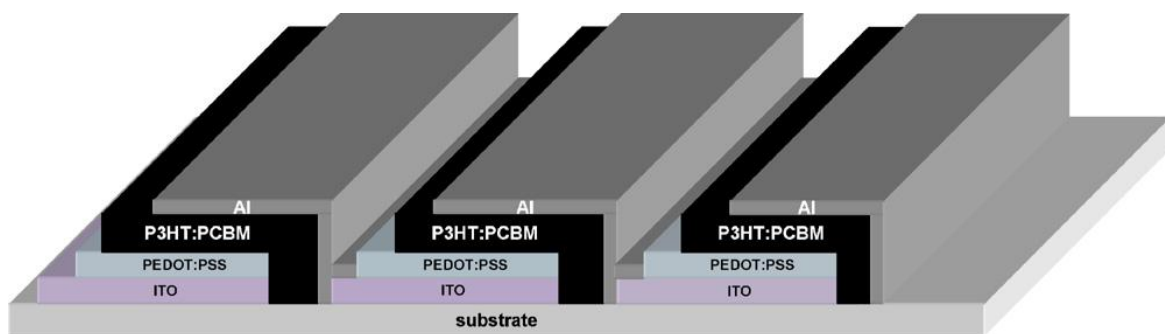


Figure 5. Series connected organic solar cells prepared on one substrate. [27]

3.2.4 Manufacturing process description

As already described in the previous chapter, the organic solar cell is a multilayer structure and thus different roll-to-roll printing or coating methods can be used for separate layers. In this chapter, a summary of the OSC manufacturing process will be described. More detailed analysis will be presented in Chapter 3. In roll-to-roll OSC manufacturing process, flexible substrate will be used as a basis. Cleaning, deionization and corona/plasma treatment will be done before the barrier layer deposition. The objective of cleaning and deionization is to remove particles and inhibit new particles to stick on the surface of the substrate. Corona/plasma treatment increases the surface energy of the substrate. As a first layer, a barrier is deposited on top of flexible substrate by coating methods since no patterning is required. Since the active materials and cathode materials are sensitive to water and oxygen, barrier inhibits those reagents to penetrate to the active regions. The barrier is dried either with hot air or UV. Registration marks will be prepared for all the layers prepared after the barrier layers since the active areas need to be aligned to each other in order to process patterned structures. Especially due to the high transparency of anode and hole injection layer, the recognition of registration marks sets challenges to the measurement equipment. On top of barrier, anode will be prepared with roll-to-roll printing methods since the anode needs to be patterned. The printed anode layer will be dried with blowing hot air or by UV. Next, hole injection layer (normally PEDOT:PSS is used) is processed by printing methods such as gravure, flexography or ink jet printing and dried with hot air. The photoactive layer is prepared with gravure, flexography or ink jet printing method due to the low solid content of the photoactive ink. Due to the sensitivity of active materials to UV, hot air will be the choice for the drying method. The top electrode i.e. cathode will be most likely to be prepared with screen printing due to the high solid content and viscosity of the cathode ink and dried with hot air. As a next step conductivity lines will be prepared in order to have contacts to anode and cathode and connect organic solar cell modules to each other. The OPV components/modules/systems will be encapsulated by using a back side barrier layer which is laminated to the plastic foil composing of other processed layers. Finally, the OPV modules/components/systems will be cut into pieces.

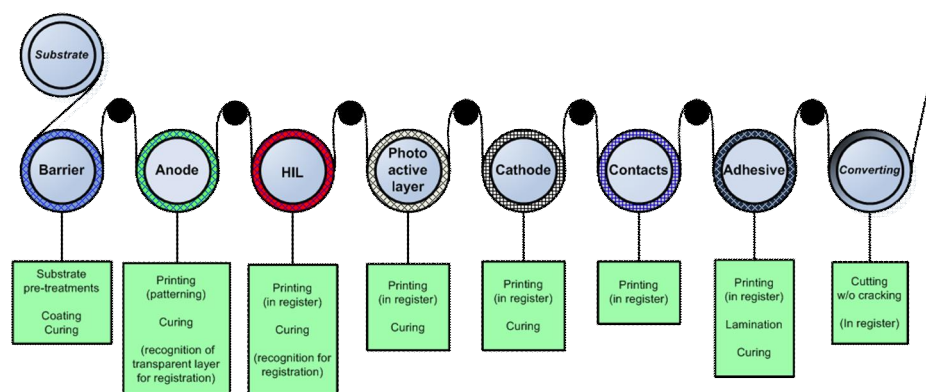


Figure 6. Process steps of OPV component manufacturing

3.3 Organic solar cells manufacturing equipment requirements

3.3.1 Technological requirements and challenges

Low cost organic photovoltaic (OPV) have been an object of intensive research during the last 10 years. Low cost can be obtained by producing organic solar cells by roll-to-roll production methods leading to mass production of organic solar cells. However, low performance and poor stability are issues that need to be solved before organic solar cells can hit into energy markets in large scale. In addition, the material costs need

to be reduced and development of materials is required in order to diminish the environmental impact of toxic materials and solvents and fulfil the environmental compliance. In addition, since one of the targets is to utilise organic solar cells in packaging industry and other consumer products, the products are required to be consumer safe. Cell efficiency has a moderated impact and monolithic cell integration slight impact on low cost solar cells.

The total lifetime of the organic solar cells is highly dependent on the shelf lifetime and operational lifetime of OPV component. In addition, the ink and material stability, especially in the case of the cathode and photoactive materials, is one of the most impacting factors which determines the total lifetime of OPV component. Furthermore, the mechanical strength has moderate effect on OPV lifetime. However, the requirements for the mechanical strength are dependent on the chosen application. Additionally, the durability of the monolithic integration affects the total lifetime.

Cell encapsulation is one of the main parameters that affect significantly on total efficiency of produced system. The development of barrier materials is needed in order to obtain a lifetime at least 1.5 years for the consumer electronic applications. Cell efficiency of separate cell either with low or high illumination affect the total efficiency obtained with whole system. The active layer of OPV device absorbs photons in certain wavelength region, so the efficiency is highly dependent on the active layer thickness. In addition, ink and material stability is of high importance when considering total efficiency. The objective is to use non-toxic materials and solvents which have moderate impact on total efficiency. The monolithic cell integration has moderate impact on total efficiency. In addition, OPV mechanical strength has slight effect.

Since the application is not defined more precisely in this report, the organic solar cell component/modules of large and small areas can be handled. Roll-to-roll processability, cell encapsulation and ink and material stability have a dominant impact on mass production of large area and small area organic solar cells. Furthermore, the total OPV thickness affect moderately on mass producible organic solar cells. With small area devices, OPV mechanical strength has a moderate effect on mass production. However, in larger areas the impact of mechanical strength is dominant. With small area devices, the components need to be monolithically integrated to other components.

The organic solar cells need to be easily integrated in other different devices in order to utilise the electrical power produced from the organic solar cells. Ease of system integration is strongly related to OPV mechanical strength and moderately related to monolithic cell integration, cell encapsulation and total OPV thickness.

3.3.2 Production process requirements and challenges

3.3.2.1 Substrate pre-treatments and converting

The plastic substrate should be as clean as possible when entering the OSC manufacturing process. Therefore, several pre-treatment steps are made to fulfil the strict cleanness requirements of the substrate. The substrate is typically first washed with water and/or solvents, such as acetone and alcohols, in an ultrasonic bath to detach and rinse away contaminants (e.g. dust, grease, debris) from the surface. The washing liquid is then evaporated. After the cleaning, static and other charges that attract contaminants and decrease runnability are removed in the de-ionization stage. These charges tend to re-develop over time. In the final pre-treatment stage, the surface energy of the substrate is increased using corona or plasma treatment to allow proper wetting, spreading, and adhesion of the material deposited in the following stages of the manufacturing. At the same time, dust is removed from the surface.

After the R2R manufacturing process of the OSC modules, converting is also necessary. Solar cells or modules are separated from each other through die cutting or slitting and cutting. After this, the cells are conveyed from the process to be packed or used. If the cells are not separated, the web material can be rewound. Converting stage might also include some cleaning, such as blowing off dust and other contaminants from the surface of the OSC.

Table 4 presents the basic properties and requirements of the plastic foil substrate. The plastic foil should be smooth and have homogeneous properties to establish a proper base for the deposition of the OSC and to maximize the cell performance. The high transparency of the plastic foil (> 80 %) ensures that light enters sufficiently into the active parts of the OSC. The surface energy is typically 20-50 mN/m but it is increased via corona/plasma treatment to allow easy deposition of the following layers. The plastic substrates withstand only temperatures that are lower than 200°C, thus this limitation needs to be taken into account in the whole OSC manufacturing process.

Table 4 Basic properties of plastic substrates.

Properties	Value	Target	Unit
Thickness	< 300	-	µm
Roughness, R_a	< 50	< 10	nm
Surface energy	20-50	> 50	mN/m
Transmission	> 80	> 90	%
Max. temperature	< 200	-	°C

The plastic foil should go through the whole OSC manufacturing process as smoothly as possible without destruction. Therefore, its runnability and stability should be maximized and static electricity minimized. Other factors affecting the R2R processability are the thickness and surface properties of the plastic foil since they influence the runnability and deposition processes, respectively.

The plastic foil forms the majority of the total thickness of the OSC. Therefore, the encapsulation quality depends significantly on the plastic foil thickness because of the fact that thicker films prevent gas permeation to a greater extent. The thickness affects also the converting processes. The high transparency of the substrate ensures maximum light entrance into the active layers of the OSC, and the high stability plays a significant role in the formation of the mechanical strength of the OSC.

Although the pre-treatment and converting stages form a base for the OSC component, they are not so important stages considering the whole manufacturing process. This results from the fact that these stages are rather optimized and highly effective. Only poor cleanness can decrease the cell performance by hindering the homogeneous deposition of the layers of the OSC and charge generation.

3.3.2.2 Front side barrier deposition and curing

Layer materials and properties

The organic materials and metal electrode materials are sensitive towards oxygen and moisture, so therefore a barrier layer is needed in the front and backside of the OPV device. Two parameters are defined in order to estimate the transmission of oxygen and moisture through the protecting layer, oxygen transmission rate (OTR) and water vapour transmission rate (WVTR). In order to reach a lifetime of 10000h, it has been estimated that the WVTR should be at room temperature at 10^{-6} g/m²/day and OTR 10^{-3} cm³/m²/day. [28]

Front side barrier layer can be formed of single layer of oxides (SiO_x , AlO_x), nitrides (SiN_x) or oxynitrides (AlO_xN_y). The main challenge in the formation of single layer barrier is that it has to be defect free in order to gain needed OTR and WVTR values. In order to decrease the paths for the moisture and oxygen to penetrate through the barrier, multilayer structures have been developed in which organic (polymer) and inorganic layers are stacked as shown in Figure 7. One option for the materials is to stack organic polyacrylate (PA) and Al or AlO_x . [29] In addition, the use of inorganic and hybrid (inorganic-organic) polymer such as silicate based materials has been reported. [30] As a front side barrier, the barrier layer needs to be as transparent as possible to the light since the absorption occurs in the active layer of the OPV device. In addition, the difference in refractive index between different layers should be low in order to avoid reflection losses. The cleanness of the processing environment is important from the viewpoint of barrier functionality, since it has been noticed that the cleanness of the processing environment correlates to the amount of cracks in the barrier film.

Table 5 Basic properties and requirements for the front side barrier layer.

Properties	Value	Target	Unit
Solids content			wt-%
Viscosity			mPa·s
Surface tension			mN/m
Thickness		> 10 μm , dependent on the requirement for OTR and WVTR	nm
Roughness		< 10 nm	%
Transmission		> 90 %	
WVTR	With conventional methods: 10-6 $\text{g}/\text{m}^2/\text{day}$ with 3-5 PA- AlO_x pairs (multilayer)	Depends on application Lifetime of 10000h at RT-> 10^{-6} $\text{g}/\text{m}^2/\text{day}$	
OTR	-	Depends on application Lifetime of 10000h at RT-> 10^{-3} $\text{cm}^3/\text{m}^2/\text{day}$	

Suitable deposition and drying methods

As already discussed, multilayer barrier structure consists of stacked inorganic and organic layers. Since there is no need for patterning the barrier layer, coating methods such as knife over coating, doctor blade coating, air knife coating etc. are suitable for deposition of the barrier layer. The coating method should be chosen considering the rheological properties of ink of the inorganic and organic materials used in the barrier layer. Coating methods can be classified to three categories which are presented in Table 6.

Table 6. Coating method classification.

Category of coating methods	Examples of the coating methods belong to the category	Characteristics
Self-metered	<ul style="list-style-type: none"> - Dip roll - Nip forward roll - Reverse roll 	<ul style="list-style-type: none"> - Wet thickness is determined the conditions of the coating meniscus
Doctored	<ul style="list-style-type: none"> - Mayer rod - Blade/knife - Air knife - Dip & scrape 	<ul style="list-style-type: none"> - Post applicator device determines the wet thickness
Pre-metered	<ul style="list-style-type: none"> - Slot die - Slide curtain - Spray 	<ul style="list-style-type: none"> - All the ink fed into an applicator is transferred to the web

In dip coating, the web is immersed in a tank of the coating material for a certain period of time. The excess material is transferred by passing the web through nip rolls or doctor blades. In knife coating techniques, the coated ink is applied directly to the substrate and spread in a uniform manner by means of a fixed knife. Knife over coating method is especially used for high viscous inks. In air knife coating, the blast of air is used to blow off the excess ink. Thus, the viscosity is much lower than in the case of knife over coating. Knife coating methods, the properties of the knife and the support roller and the gap between the knife and the substrate play a key role in the formation of uniform barrier layer. In pre-metered methods, all the ink which is fed into an applicator is transferred to a web forming a wet coating.

Since there are a high variety of barriers materials, the certain coating methods for the barrier materials can not be defined. Therefore, in Table 7, the advantages and disadvantages of coating methods in general are summarised considering the requirements set by the process of barrier layer.

Table 7. Advantages and disadvantages of coating methods.

Printing method	Advantages		Disadvantages
Coating	<ul style="list-style-type: none"> - Large uniform coated areas - Defect free layer 	<ul style="list-style-type: none"> - Layer uniformity - Large area printing - High viscosity range (different methods can be used) 	<ul style="list-style-type: none"> - Material consumption - No patterning possibility

Production process challenges

The operating and shelf lifetime of OPV component are highly dependent on the properties of the barrier film. WVTR and OTR are key parameters that define the properties of the cell encapsulation. In addition, these parameters affect on the cell efficiency since the active materials and metal electrode materials are sensitive to oxygen and moisture. The barrier needs to transparent (>85 %) as possible to avoid reflections of light. Low transparency diminishes the cell efficiency of the OPV component since part of light does not exceed the active layer in which the absorption should occur.

Barrier surface properties in terms of low amount of impurities, low surface roughness affect the cell encapsulation. In addition, the thermal and mechanical properties of the barrier have an effect on encapsulation as well. The solvents for the barrier ink should

be chosen in order to take into account the plastic foil beneath and the layers processed on top of the barrier. The layers and materials need to be chemically compatible i.e. the layer processed on top cannot dissolve the layer beneath.

The properties of the flexible substrate i.e. plastic foil play a key role in a formation of defect free, homogenous barrier layer. The surface roughness (rms) of the plastic foil should be less than $< 1\text{nm}$ and free of spikes greater than tens of nanometres. [29] In addition, the surface should be free of impurities. The surface energy of the plastic foil needs to be higher than the surface tension of the inorganic barrier material ink in order to wet the ink properly on the surface. In addition, the flexible substrate needs to withstand the solvents used in barrier material inks. Furthermore, the mechanical properties of the plastic foil and thickness of the plastic foil are of importance since no cracks are allowed in the barrier layer.

Nowadays, the single layer and multilayer barrier films are deposited with low pressure gas phase technologies such as sputtering, evaporation and plasma enhanced chemical vapour deposition (PECVD). These processes require costly equipment and the used systems are very complex, so there is a need for development of low cost production methods for barrier layers. [29] The main challenge in the wet deposition methods is the R2R printing/coating of uniform layer without any cracks and pinholes which form a path to moisture and oxygen to penetrate to the OPV structure. This is one of the main challenges in the whole OPV manufacturing process, since the encapsulation is dominant factor affecting the shelf and operating lifetime of the OPV component. The coating method should be chosen according to the ink properties. Since the barrier layer consisted of several layers, different coating/printing methods can be used for organic and inorganic layers. Due to the high requirements for homogeneity of the barrier layer (OTR and WVTR), a lot of effort is needed for the optimisation process of the ink formulation and printing/coating processes. The layer thickness of the barrier layer and ink properties in terms of chemical compatibility, viscosity and surface tension correlate directly to the WVTR and OTR values. Furthermore, the layer thickness of the barrier layer should be optimised. If the barrier layer is too thick, it might form mechanical stress and thus cracks to the barrier layer. The barrier layer properties in terms of chemical compatibility, surface roughness, and surface energy affect the ink properties of the anode layer.

Hot air drying is the main method to cure the stack of inorganic/organic barrier layers. In addition, UV curing could be used for the front barrier layer since no UV sensitive active layers are present in the structure in this process phase. The drying temperatures should be chosen taken into account the thermal properties of the barrier material and the thermal stability of the plastic foil. Drying is an important processing step, since too high temperature easily causes cracks on the barrier layer. The main factor affecting the drying time is the thickness of the wet film. The layer should be dry in order to avoid oxygen and moisture to penetrate to the other layers processed as a next step. The challenges and solutions are summarised in Table 8.

Table 8. Challenges and solutions for the front side barrier layer.

Challenges	Solutions
<ul style="list-style-type: none"> - Uniformity (pinhole free, no cracks) of the barrier layer - Suitability of coating and printing methods (non-vacuum processes) for processing barrier layers with high requirements for OTR and WVTR 	<ul style="list-style-type: none"> - Barrier material development for non-vacuum processes - Ink and drying procedure optimisation

3.3.2.3 Anode patterning and curing

Layer materials and properties

The anode layer made of indium tin oxide (ITO) is typically deposited using sputtering or evaporation followed by a separate patterning stage, such as etching or embossing. Therefore, additive patterning, such as printing, would be a more preferable deposition method in decreasing the number of process steps. ITO nanoparticles are dispersed into various alcoholic or aqueous solvents with small amounts of binders and additives. [31-33] The ITO content is 40-60 wt-%, and the drying and flow properties of the anode ink are adjusted by using at least two different solvents having different rates. In order to maximize both the printability and conductivity of the anode, the amount of binder and additives should be optimized. Due to the high cost and brittleness of the ITO layer and the poorer print quality than required, significant ink and process developments have to be performed.

The viscosity of the anode ink is 10-70 mPa·s depending on the nanoparticle content. [31-33] The ink formulation needs to be optimized to prevent both excessive spreading and poor levelling. High conductivity and transparency of the anode ensures a high OSC performance. However, the anode conductivity is often rather low (0.5-5 kΩ/sq) due to the porous nature of the nanoparticle layer although nanoparticles decrease the curing temperature and light scattering and increase the resolution. The transmission of the anode should be over 80 % to ensure proper light absorption into the photoactive layer of the OSC. By using inert atmosphere during the deposition, the conductivity improves but the R2R processability might suffer.

The anode layer should be smooth, uniform, and homogeneous to maximize the conductivity and transparency and to decrease the amount of short circuits. [31-33] The optimum layer thickness is 500-800 nm but it might be difficult to achieve at one pass when using low viscosity inks. In addition, the pattern should have excellent resolution (10-40 μm) and register as well as sharp edges. However, these requirements are not yet reached with printing since the maximum print resolution is currently around 40-100 μm. The surface energy of the ITO anode layer is approximately 40 mN/m but it is increased to 60-70 mN/m using corona/plasma treatment to enable proper deposition of the following hole injection layer. Table 9 shows the properties of the ITO anode and the future targets.

Table 9. Properties and requirements for the ITO anode ink and layer.

Properties	Value	Target	Unit
Solids content	40-60	-	wt-%
Viscosity	> 10	-	mPa·s
Surface tension	40	60-70	mN/m
Thickness	100-1000	500-800	nm
Roughness	> 100	< 5	nm
Transmission	> 80	> 90	%
Resistance	0.5-5	< 0.05	kΩ/sq
Resolution	40-100	10-40	μm

Another approach for the transparent anode is to pattern a silver metal grid and deposit a highly conductive and transparent organic polymer layer on top. [33-36] The metal grid increases the conductivity of the anode to a desired level. Silver inks are commercially available for most of the printing methods as a result of which the ink and layer properties depend on the printing method. The solids content is typically 10-60 wt-%, resolution 40-100 μm and viscosity over 10 mPa·s. The optimum thickness of the metal grid is 100-200 nm but currently it lies between 200 and 500 nm. The metal particles of the ink tend to agglomerate which increases the surface roughness of the grid. Optimizations and compromises are required to achieve both high conductivity and transparency. For example, the spacing between the grid lines should be ten times larger than the line width to obtain high transparency and relatively high conductivity.

The conductive organic polymer layer is typically made of PEDOT:PSS which is an aqueous solution having low solids content (1-4 wt-%) and high surface tension. [32-36] Polar co-solvents and additives are often added to increase the printability but this occurs at the expense of the solids content and conductivity of the ink. Currently, PEDOT:PSS inks are also available for screen printing with rather high solids content (4-10 wt-%) and viscosity (>8000 mPa·s). More information about PEDOT:PSS inks is presented in the Chapter 3.2.4. The organic layer should be smooth and uniform and be able to smoothen and completely cover the metal grid. The thickness should be 150-200 nm but in the case of low solids content the transfer volume needs to be high, thus making the control of the ink flow difficult. The properties and future targets of the metal grid and polymer layer are presented in Table 10.

Table 10. Properties and requirements for the metal grid and conductive organic polymer inks and layers.

	Metal grid		Conductive organic polymer		Unit
	Value	Target	Value	Target	
Solids content	10-60	-	1-10	> 5	wt-%
Viscosity	>10	-	< 30	> 50	mPa·s
Surface tension	25-35	> 40	30-70	< 40	mN/m
Thickness	200-500	100-200	150-200		nm
Roughness	30-60	< 5	< 30	< 5	nm
Transparency	> 80	> 90	> 90		%
Conductivity	> 0.05	< 0.05	1-10	< 0.5	kΩ/sq
Resolution	40-100	10-20	-	-	μm

Suitable deposition and drying methods

The most suitable printing methods for the ITO anode are gravure, flexography, inkjet, and screen printing whose advantages and disadvantages are presented in Table 11. Gravure, flexography, and inkjet use low viscosity inks as a result of which thin and

levelled layers are obtained. However, their excessive spreading and low thickness might decrease the resolution. Screen printing, for its part, can deposit thick layers using higher viscosity inks but the resolution is poor.

Flexography uses low nip pressure so that underlying layers are not destroyed or damaged during the anode deposition. In addition, the ink transfer amount is easily adjusted and controlled. On the other hand, the poor resolution and register decrease its suitability. Gravure printing produces high resolution at high speed and the ink transfer is adjustable and controllable. However, solid tones are reproduced via ink spreading and ink is not always transferred from all of the cells, which might lead to levelling problems and pinholes. The high nip pressure might also damage underlying layers. Inkjet is a non-contact method having a high resolution but it suffers from nozzle clogging and low printing speed. Nanoparticles agglomerate easily, thus clogging the nozzles, and the print resolution decreases with increasing speed. Screen printing uses also low printing pressure but the resolution is too poor.

Table 11. Advantages and disadvantages of the potential deposition methods for ITO anode.

Printing method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - Low nip pressure - Adjustable ink transfer 	<ul style="list-style-type: none"> - Poor resolution and register - Thin layer
Gravure	<ul style="list-style-type: none"> - High resolution - Adjustable ink transfer - High speed 	<ul style="list-style-type: none"> - Solid tones reproduced via ink spreading - Ink transfer problems - Thin layer - High nip pressure
Inkjet	<ul style="list-style-type: none"> - High resolution - Non-contact 	<ul style="list-style-type: none"> - Low speed - Nozzle clogging - Thin layer
Screen printing	<ul style="list-style-type: none"> - Low pressure - Thick layers 	<ul style="list-style-type: none"> - Poor resolution

Silver metal grid has to have high resolution and low thickness. Therefore, the most suitable printing methods are gravure, flexography, inkjet, and offset. Gravure, flexography, and inkjet use low viscosity inks that spread easily whereas offset uses pasty high viscosity inks that spread less. On the other hand, offset produces rough ink layers due to the ink layer splitting during the ink transfer. This decreases both the transparency and conductivity of the anode. Offset also uses dampening water that might cause problems with conductive inks but waterless process is also available.

The organic conductive layer is thin and smooth and covers the metal grid completely. This is mainly achieved by using low viscosity inks, thus the main deposition methods are gravure, flexography, and inkjet. The low viscosity and solids content of the PEDOT:PSS inks require high transfer volumes which makes the control of the ink flow difficult when printing thicker layers than 100 nm. Screen printing can use high viscosity inks but the thickness is too high for this layer although thicker layers would cover the metal grid and its roughness completely and still form a smooth layer. The advantages and disadvantages of the deposition methods of the metal grid and the polymer layer are shown in Table 12.

Table 12. Advantages and disadvantages of the potential deposition methods for metal grid and conductive polymer layer.

Printing method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - Thin layer - Low viscosity inks - Low nip pressure - Adjustable ink transfer 	<ul style="list-style-type: none"> - Poor resolution and register - Excessive spreading
Gravure	<ul style="list-style-type: none"> - Thin layer - Low viscosity inks - High resolution - Adjustable ink transfer 	<ul style="list-style-type: none"> - Solid tones reproduced via ink spreading - Ink transfer problems - Excessive spreading - High nip pressure
Offset	<ul style="list-style-type: none"> - Thin layer - No excessive spreading - High resolution 	<ul style="list-style-type: none"> - High viscosity inks - Ink layer roughness - High nip pressure
Inkjet	<ul style="list-style-type: none"> - Thin layer - Low viscosity inks - High resolution - Non-contact 	<ul style="list-style-type: none"> - Low speed - Nozzle clogging - Excessive spreading
Screen printing	<ul style="list-style-type: none"> - Commercially available inks - Low pressure - Thick layers → covers roughness 	<ul style="list-style-type: none"> - High viscosity inks - Thick layers - Poor resolution

The anode layer can be dried by blowing hot air onto its surface to evaporate solvents. The drying temperature is 120-140 °C. This stage can also sinter the layer to some extent to increase its conductivity. PEDOT:PSS layer can be dried using lower temperatures (80-140 °C). The anode inks are also often UV-curable to increase their adhesion to the substrate. In this case, the ink contains binders that polymerize under UV light in the presence of photo-initiator additives.

Production process challenges

The anode layer should be as conductive as possible to enable efficient charge transport and generation in the cell, thus increasing the OSC efficiency and lifetime. Thus, the anode layer should be smooth, uniform, and homogeneous since unevenness and roughness decrease the conductivity and transparency. In addition, the OSC performance decreases if the resolution is poor and the edges are not sharp. Inert processing conditions can increase the conductivity by preventing the anode oxidation but this might cause problems in R2R processes. Current anodes have low conductivity and printing cannot reproduce the strict resolution requirements. Consequently, the printing process and inks require further developments.

Anode materials are highly transparent as a result of which light is conveyed reliably into the active layers of the OSC. Thus, the transparency has a smaller effect on the cell performance than the conductivity. However, some developments are still required to optimize the conductivity and transparency in the case of the metal grid based anode. To obtain high efficiency, R2R processability, and mechanical strength of the OSC, the anode should also be stable. The anode should withstand any deposition and drying stages without dimensional changes or damages and be chemically compatible with all the inks deposited after it.

The thickness of the anode affects also the OSC manufacturing and performance. Too thick anode layers can crack or increase the rigidity or brittleness of the OSC, thus decreasing runnability and changing conductivity. The smoothness and cleanness of the

anode layer enable high conductivity and low light scattering as well as proper deposition of the hole injection layer (HIL). Due to the rather low viscosity of the anode ink, these properties are easily achieved, thus leading to high cell efficiency and lifetime. In addition, the surface energy of the anode layer is higher than the surface tension of the HIL ink due to the corona/plasma treatment. This ensures proper HIL ink deposition onto the anode layer.

The anode ink properties do not also affect the OSC performance. The ink viscosity is adjustable and the surface tension of the ink always lower than the surface energy of the barrier layer due to the corona/plasma treatment of the barrier layer, thus ensuring proper wetting and spreading of the anode ink. Furthermore, the plastic substrate should withstand the deposition and drying/curing of the anode layer without destruction and the barrier layer should be stable in order to achieve a good OSC performance.

The deposition and drying of the anode is extremely critical in the OSC manufacturing process since the layer conductivity and stability determine the OSC performance to a great extent. In addition, this layer should give a proper base for the following layers and be chemically compatible with them. The challenges of the anode layer as well as some possible solutions are presented in Table 13.

Table 13. Challenges of the anode layer and the solutions.

Challenges	Solutions
<ul style="list-style-type: none"> - Low conductivity - Poor stability - Layer homogeneity and roughness - Chemical compatibility - Thickness and resolution requirements 	<ul style="list-style-type: none"> - Printing process optimization - Material development and ink formulation - Inert processing

3.3.2.4 Hole injection layer patterning and curing

Layer materials and properties

The hole injection layer (HIL) smoothen the anode layer and enhance the OSC performance by creating a proper interfacial contact between the anode and photoactive layers, i.e., facilitating the charge transport. [32,37-42] Typically, low conductive PEDOT:PSS is used in printing applications due to its proper conductivity, transparency, and stability. PEDOT:PSS is an aqueous solution having a low solids content (1-3 wt-%) and high surface tension. Polar co-solvents (5-30 wt-%), conductivity enhancers (0-5 wt-%), and surfactants (<1 wt-%) are typically added to increase the material printability. However, this decreases the solids content (<1 wt-%) and electrical performance of the ink. The most common co-solvent is isopropanol (IPA) that decreases the surface tension of the ink to 30-40 mN/m and increases the viscosity to 10-30 mPa·s. As a result, the ink wetting, spreading, and printability improve but the ink drying characteristics change significantly. The resistivity of the HIL is 500-5000 Ωcm.

Table 14. Properties and requirements for the hole injection layer.

Properties	Value	Target	Unit
Solids content	< 3	> 5	wt-%
Viscosity	< 30	> 20	mPa·s
Surface tension	30-70	< 40	mN/m
Thickness	40-100	< 50	nm
Roughness	1-30	< 5	nm
Transmission	> 90		%
Resistivity	500-5000		Ωcm
Register	Depends on the module design	100-200	μm

The hole injection layer should be thin, smooth, homogeneous, and uniform. [32,37-43] The thickness ranges from 40 to 100 nm depending on the deposition method, ink properties, and ink transfer efficiency. It is preferable to have as thin layer as possible to prevent any extra charge transport losses. The HIL should also be as transparent as possible to allow large current density and maximum light absorption into the active layer. The main properties and requirements of the HIL are shown in Table 14.

Suitable deposition and drying methods

Gravure, flexography, and inkjet are the most suitable deposition methods for the HIL due to the low ink viscosity, solids content, and layer thickness. In addition, the water-based ink with polar co-solvents does not cause damages to the printing presses and materials. However, in order to prevent excessive ink spreading, the printing speed should be rather high and the ink transfer volume low. The low ink transfer volume can be obtained by using smaller cells in the printing cylinder (gravure) or in the anilox roller (flexography) or creating smaller droplets (inkjet). HIL is deposited as a solid patch on top of the anode, thus eliminating strict resolution and register demands. The advantages and disadvantages of the different printing methods are shown in Table 15.

Flexography uses low nip pressure during the ink transfer so that underlying layers are not damaged. The ink transfer is efficient since ink spreads and forms a uniform layer already onto the plate surface prior to the transfer onto the substrate. The ink transfer amount is adjusted by changing the cell volume of the anilox roller. However, the poor print resolution and register might cause problems in the deposition of HIL.

Inkjet is a non-contact method with high print quality but it suffers from nozzle clogging and low printing speed. HIL ink contains polymers that can easily agglomerate and clog the nozzles. In addition, the print resolution decreases significantly as the printing speed increases, thus creating pinholes.

Gravure has high print quality and printing speed. The amount of ink transfer can also be adjusted by changing the cell dimensions of the printing cylinder. Solid tones are reproduced via ink spreading which can lead to excessive or incomplete spreading. In addition, ink is not always transferred from all of the cells which cause missing dots and pinholes. Gravure also has extremely expensive cylinders and the nip pressure is rather high.

Table15. Advantages and disadvantages of the different deposition methods for the hole injection layer.

Printing method	Advantages		Disadvantages
Flexography	- Thin ink layer - Low viscosity	- Cheap printing plates - Low nip pressure - Accurate and adjustable ink transfer	- Poor resolution and register
Inkjet		- Non-contact (no pressure) - High quality	- Low speed - Nozzle clogging
Gravure		- High quality - High speed - Adjustable ink transfer	- Expensive printing cylinders - Solid tones reproduced via ink spreading - Ink transfer problems - High nip pressure

The hole injection layer is dried by blowing hot air onto its surface to remove water and co-solvents. The drying temperature is typically 80-140 °C depending on the substrate and printing speed. The fast evaporation of IPA and slow removal of water create challenges to the drying process and make the OSC performance lower.

Production process challenges

The surface properties and thickness of the HIL do not affect the OSC performance since the dilute and low viscosity water-based ink creates a thin, smooth, and uniform layer having a high surface energy. This high surface energy ensures excellent wetting, spreading, and adhesion of the low surface tension photoactive ink, thus ensuring good OSC performance. However, the control of the printing process might be difficult as a result of which the print quality and OSC performance might suffer. In addition, the ink transfer process affects the layer quality.

The high surface tension of the hole injection ink has a significant effect on the OSC efficiency. This surface tension should be lower than the surface energy of the anode to obtain good ink wetting and spreading as well as printability. Since the surface energy of the anode is often quite low, it has to be increased with corona/plasma treatment or the surface tension of the HIL ink lowered using co-solvents. The latter technique requires heavy ink formulation and optimization.

The drying of the water-based HIL ink is also difficult since it is difficult to remove water (much energy needed) from the ink layer and the polar co-solvents evaporate fast. This increases the layer unevenness and decrease the OSC performance. By using higher drying temperatures or lower printing speed the efficiency of the drying process is improved but too high temperature can damage the substrate and too low speed can lead to excessive ink spreading. The ink formulation may also improve the drying process.

The HIL conductivity and uniformity has an effect on the OSC lifetime since the charges have to flow easily between the anode and the photoactive layer. High conductivity improves the OSC performance and high uniformity the stability of the charge transfer. This layer should also withstand strong solvents used in the following deposition processes (mainly photoactive and cathode inks) since strong solvents can destroy this thin layer completely fast.

The printing of the HIL is highly important considering the whole OSC manufacturing process since it determines the charge carrying ability of the OSC. In addition, the high surface tension of the ink and difficulties in drying make the printing process control difficult and challenging on top of the anode. On the other hand, the layer properties affect the OSC performance only moderately due to its thinness, smoothness, and uniformity. Table 16 presents the main challenges of the HIL deposition and possible solutions.

Table 16. Challenges of the hole injection layer and the possible solutions to the problems.

Challenges	Solutions
<ul style="list-style-type: none"> - High surface tension - Low viscosity and solids content → poor printability - Drying 	<ul style="list-style-type: none"> - Ink formulation and optimization - Higher viscosity - Alternative co-solvents/PEDOT:PSS dispersions

3.3.2.5 Photoactive layer patterning and curing

Layer materials and properties

The photoactive layer absorbs light and creates charges that flow through the layer to the electrodes, thus producing electricity. [11,15-18,21-25] The photoactive layer comprises of a blend of semiconductive polymers and fullerenes at the interfaces of which the charge transfer takes place. These photoactive materials are dissolved/dispersed into non-polar solvents to make them solution-processable, i.e., printable. The solvents are typically chlorinated, such as dichlorobenzene, chlorobenzene or chloroform. The solubility of the active materials is rather poor due to which the inks are extremely dilute and have low viscosity of 1-30 mPa·s. The properties and future targets of the photoactive layer are presented in Table 17.

Table 17. Properties of the photoactive layer and its requirements.

Properties	Value	Target	Unit
Solids content	1-3	> 5	wt-%
Viscosity	< 30	> 20	mPa·s
Surface tension	25-40	-	mN/m
Thickness	80-300	-	nm
Roughness	< 30	< 5	nm
Register	Depends on the module design	100-200	μm

The photoactive layer should be smooth, homogeneous, and uniform and its thickness 80-300 nm. [32,37-40,43-47] The absorption maxima, i.e., the layer thicknesses where the cell efficiency reaches its maximum level, are approximately 90 nm and 250 nm. The low thickness requirement results from the poor mobility ($\sim 0.1 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$) of the organic semiconductors. The layer has to be smooth (< 20 nm) to allow proper light absorption without scattering.

Suitable deposition and drying methods

Due to the low ink viscosity, solids content, and ink layer thickness, gravure, flexography, and inkjet are the best alternatives for the deposition of the photoactive layer (Table 18). In order to prevent excessive spreading of the low viscosity ink, the printing speed should be rather high and the ink transfer volume small.

Flexography uses cheap printing plates that decrease the costs of the OSC manufacturing process. In addition, the low nip pressure ensures that underlying layers are not damaged during printing and the accurate, adjustable, and efficient ink transfer improves layer uniformity and control. On the other hand, the printing plates have poor solvent resistance as a result of which chlorinated solvents can damage the plate. In addition, the print quality (mainly resolution) and register are rather poor. By developing new plate materials with higher chemical resistance and resolution, optimizing the ink transfer, and using anilox rollers with small and low volume cells, flexography can become more suitable for the deposition of the photoactive layer.

Inkjet, for its part, is a non-contact method with high resolution. This eliminates the effect of the nip pressure on the OSC structure and performance and reduces the amount of waste. The final print quality is determined by the surface chemistry of the photoactive ink and the jetting parameters. Chlorinated solvents may cause damages to the print head electronics and because of the poor solubility of the photoactive materials, the ink may contain large clusters that clog the nozzles. This drawback can be conquered by developing new photoactive materials with higher solubility. However, the print resolution and quality decreases at high speeds, thus significant process developments are still needed.

Gravure offers a high print quality and a high speed and volume production with adjustable ink transfer. The printing cylinder has superior chemical resistance also to chlorinated solvents. However, the printing cylinders are expensive and solid tones are reproduced via ink spreading. This ink spreading places great demands towards the control of ink-substrate interactions, ink transfer, ink properties, and printing conditions. Gravure printing suffers also often from incomplete ink transfer that creates pinholes. The ink spreading can be controlled by using higher printing speeds and lower cell volumes. Because of the excellent chemical resistance, high print quality, and high printing speed, gravure would be the best choice for the deposition of the photoactive layer.

Table 18. Advantages and disadvantages of the different deposition methods for the photoactive layer.

Printing method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - Thin ink layer - Low viscosity 	<ul style="list-style-type: none"> - Cheap printing plates - Low nip pressure - Accurate ink transfer
Inkjet		<ul style="list-style-type: none"> - Non-contact - High quality
Gravure		<ul style="list-style-type: none"> - High quality - High speed - Superior chemical resistance - Adjustable ink transfer

The photoactive layer is typically dried by blowing hot air onto its surface, which causes the ink solvent to evaporate. Typically, the drying temperature is 100-140 °C depending on the process speed, substrate, and ink solvents. During drying, the ink layer thickness decreases significantly since most of the ink volume (solvent) is removed from the ink layer.

Production process challenges

The photoactive layer should be thin enough to maximize the light absorption and charge generation (OSC efficiency) and to decrease process costs. However, with thin layers the printability and layer uniformity degrade because of more difficult and uncontrolled ink transfer. This decreases the OSC efficiency and lifetime. On the other hand, thick layers can crack during winding or decrease the bending capability of the OSC cell, thus causing problems in R2R processability and lifetime. The main challenge is to optimize both the printability and light absorption capacity by changing the ink properties.

The surface energy of the photoactive layer should be higher than the surface tension of the cathode ink to enable proper wetting and uniform spreading of the cathode ink. It is also advantageous to have a smooth, uniform, and clean surface and homogeneous layer structure to avoid light scattering, maximize light absorption as well as charge generation, and increase adhesion of cathode to the photoactive layer. The final layer structure is determined during drying when most of the ink volume is removed via evaporation but ink properties and composition determine mainly the surface chemistry of the photoactive layer.

The photoactive ink contains typically chlorinated solvents that are toxic and harmful to the environment. Due to the low solids content of the ink, the relative amount of solvent removed during drying is extremely large. Therefore, effective recovery systems are required. Alternative solvents and higher solids content reduce the need for the recovery and improve printability and print quality but the poor solubility of the material limits this. The increase in the solids content might also increase the layer thickness so that the OSC performance decreases. The chemical compatibility of the photoactive ink with previous layers is utmost important so that the ink does not dissolve or damage any of the underlying layers. The photoactive layer should also remain stable under any mechanical or thermal stresses encountered during the printing and drying processes.

The surface tension and viscosity of ink have only a moderate effect on the OSC performance. The surface energy of the HIL (water-based ink) is always higher than the surface tension of the photoactive ink (solvent-based), thus resulting in spontaneous wetting and spreading and good print quality. Together with the low ink viscosity, which makes the ink flow more easily, and the smooth and uniform surface of the HIL, a uniform, smooth, thin, and homogeneous photoactive layer is commonly formed. On the other hand, the lower the viscosity, the more the ink spreads and more difficult is the control of the print quality.

The plastic substrate should withstand the drying temperature of the photoactive layer to avoid register, runnability, and printability problems in the manufacturing process. In addition, the cleanness and stability of HIL should be controlled and the cathode ink and bus bars/contact pads as solvent-based materials chosen carefully to obtain fully functional OSC and prevent print quality as well as adhesion problems.

As the whole OSC process is considered, the deposition and drying of the photoactive layer is not as significant as the deposition of the other layers. This results from the rather easy deposition and good printability of the photoactive ink on the top of the HIL. Therefore, the deposition of the other layers is more challenging and can cause bottlenecks in the manufacturing process. Table 19 presents the main process challenges and possible solutions to them.

Table 19. Challenges of the photoactive layer and the possible solutions.

Challenges	Solutions
<ul style="list-style-type: none"> - Low solids content and solubility - Chlorinated solvents → recovery system - Low viscosity and thin layer → poor printability - Low surface energy - Control of the surface properties 	<ul style="list-style-type: none"> - Higher solubility materials - Non-chlorinated solvents - Ink transfer control - Ink optimization - Higher surface energy (ink composition, surface treatment)

3.3.2.6 Cathode patterning and curing

Layer materials and properties

Cathode determines the amount of electrons injected into the photoactive layer and hence the OSC efficiency. [32,34,40,45,48-52] The work function of the cathode material is typically low or matches with that of the photoactive layer to improve the OSC performance. A thin, low work function electron transport layer is often deposited between the patterned cathode and the photoactive layer to prevent interfacial mixing of these layers, improve the cathode printability, protect the photoactive layer from oxidation, and increase the OSC efficiency.

Aluminium and silver are the most commonly used cathode materials used in the printing applications due to their high conductivity. [32,34,40,45,48,52] Silver inks are commercially available but their high work function, low surface tension, and expensiveness cause severe deposition and operation problems. The work function of aluminium is low and matches perfectly with that of the P3HT:PCBM photoactive material, thus forming ohmic contact. However, aluminium inks are still under development. Typically, non-polar solvents are used which decreases the surface tension of the ink to 25-35 mN/m. Consequently, printability and wetting problems occur when printing on low surface energy photoactive layer. By increasing the amount of binders and additives, the printability improves but at the same time the conductivity decreases dramatically.

The cathode is often deposited on top of the electron transport layer. [32,34,45,48,52] The printed layer should be homogeneous to ensure excellent conductivity. The high conductivity and OSC efficiency is also obtained by using high solids content inks (10-50 wt-%) which increases the layer thickness (1-10 μm) and ink viscosity (> 200 mPa·s). However, in some printing applications, the viscosity has been 5-20 mPa·s. Properties and future targets of the cathode layer are collected into Table 20.

Table 20. Basic properties and requirements of the cathode.

Properties	Value	Target	Unit
Solids content	10-60	> 60	wt-%
Viscosity	> 5	> 200	mPa·s
Surface tension	25-35	-	mN/m
Thickness	1-10	~ 1	μm
Roughness	1	< 0.1	μm
Resistance	>10	Min.	mΩ/sq
Register	Depends on the module design	100-200	μm

Typical electron transport materials include Ca, Li, LiF, ZnO, and TiO_x and some of them can be made printable. [32,34,45,48-52] These materials are often dissolved into polar solvents to improve the wetting and spreading of the cathode ink and to prevent dissolution of the photoactive layer. Electron transport materials tend to oxidise easily and they are reactive towards many materials, which limits the choice of solvents. The electron transport layer should be thin, smooth, and uniform to increase the OSC performance. Depending on the deposition method, the thickness ranges from 5 nm to 150 nm but the optimum thickness is 5-10 nm since thicker layers increase the resistance and cause losses in the cell efficiency. Therefore, the ink should have low viscosity.

Suitable deposition and drying methods

The most suitable method for the cathode deposition is rotary screen printing. Screen printing produces thick ink layers with high conductivity using high solids content and viscosity inks. In addition, the low printing pressure ensures that underlying layers are not damaged during the cathode deposition. On the other hand, the print resolution is rather poor which might cause problems with small OSC sizes. If the resolution requirements are too high for screen printing, gravure, flexography, and inkjet might be used but these methods use low viscosity inks that can spread extensively and produce thin layers. Evaporation might also be used together with some patterning method, such as embossing or laser patterning but this increases significantly the complexity of the manufacturing process. Due to the fact that the inks are still under development, printing problems such as screen blocking, pinholes and too fast drying are easily formed. Table 21 shows the main advantages and disadvantages of different deposition methods.

Table 21. Advantages and disadvantages of the different deposition methods for the cathode.

Printing method	Advantages	Disadvantages
Flexography	- High resolution	- Thin layer - Low viscosity inks
Inkjet		
Gravure		
Screen printing	- High solids content - Thick layer - High viscosity - Low pressure	- Screen blocking - Low resolution
R2R evaporation	- High resolution - Homogeneous and thin layer	- No patterning/complex process with patterning

The electron transport layer can be deposited using inkjet, gravure, or flexography since the layer needs to be thin and homogeneous and the ink viscosity is low. Particle agglomeration may cause severe clogging problems in the case of inkjet. Some solvents might dissolve flexographic printing plates but the use of polar solvents eliminates this problem nearly completely.

The cathode and electron transport layer are both dried and sintered to obtain homogeneous layers. During drying, the ink solvent evaporates after which in the sintering stage the metal particles coalesce, thus forming a uniform film with high conductivity. Typical temperatures are 60-150 °C. In order to achieve complete sintering at these rather low temperatures, nanoparticles are used.

Production process challenges

Cathode inks use non-polar solvents that are often harmful to the environment and may dissolve underlying layers. Therefore, recovery systems are required but the relatively

low amount of solvent makes the system lighter than in the case of the photoactive layer. Finding of alternative solvents and further ink development can improve the deposition process and OSC performance. The cathode ink properties have only a moderate effect on the OSC performance. The high viscosity decreases ink spreading and ensures its accurate deposition. Furthermore, the low surface tension enables excellent wetting, spreading, and adhesion of the ink. The chemical stability of the ink, for its part, affects the stability of the OSC.

The thickness of the cathode layer affects the OSC lifetime since it protect the photoactive layer from oxidation. The surface of the cathode layer oxidises rather easily and forms a rather stable, protective layer. The thicker the layer, the less oxygen gets into contact with the photoactive layer. With thinner layers, the whole cathode might oxidise, thus forcing the photoactive layer into contact with air. On the other hand, inert atmosphere is often required, thus making the construction of the printing press more complicated. The relatively high thickness of the cathode affects also the total active layer thickness, the total OSC thickness, and the R2R processability.

The conductivity of the cathode should be as high as possible to obtain long OSC lifetime and high OSC efficiency. The final structure of the cathode layer (morphology and topography) is determined in the sintering stage where individual metal particles coalesce, thus forming as homogeneous layer as possible. This can be obtained by deposition thick layers using inks with high metal content but too thick layer might also prevent complete sintering by hindering the sintering energy convection into the layer. In addition, the plastic substrate and underlying layers do not withstand high temperatures required for complete sintering. These factors increase the risk for inhomogeneous and porous cathode layer and lead to decreased efficiency and lifetime. Alternative sintering processes (e.g. laser sintering), sintering process developments, printing process optimizations, and ink formulation can improve the layer conductivity.

The cathode layer smoothness and surface energy affect the ink flow of the following layers, such as contact pads or bus bars and adhesive layer, whereas the surface cleanness ensures stable OSC operation. The mechanical and chemical stability of the cathode has significant effect on the OSC lifetime and efficiency, R2R processability, and mechanical strength. The surface chemistry as well as roughness of the photoactive layer should allow proper wetting and spreading of the cathode ink.

Considering the whole OSC manufacturing process, the deposition and drying of the cathode are highly important since they determine the conductivity, stability, and thickness of the cathode layer. These factors have extremely high influence on the OSC performance. Due to the fact that the ink development is still ongoing and the printing and drying processes require optimization, homogeneous layers are rather difficult to be produced, making this process stage a bottleneck in the OSC manufacturing. The main challenges and solutions are presented in Table 22.

Table 22. Challenges of the cathode layer and solutions.

Challenges	Solutions
<ul style="list-style-type: none"> - Toxic solvents - Homogeneous layer - Conductivity, stability - Thick layer 	<ul style="list-style-type: none"> - Alternative solvents - Ink formulation → printability vs. efficiency - Optimized sintering and printing process - Inert atmosphere

3.3.2.7 Contact pads and bus bars (metallization) deposition and curing

Layer materials and properties

Contact pads and bus bars (metallization) are needed to prepare an anode and cathode contact from the OPV component/module and connect it to other OPV components/modules or other components such as batteries in order to store the created electricity. The main property of the materials used for metallization is high conductivity. Therefore, high conductivity metals such as silver, aluminium, copper can be used for preparing the metallization. [53] The current status in the development of high conductivity inks was already described in the previous Chapter 3.2.9, so it will be discussed only briefly in this chapter. The silver nanoparticles are most commonly used material for the metallization of components for printable electronics. The particle size is ranging from several nanometres to hundred nanometres which enable sintering in low temperatures suitable for plastic electronics. [54]

The layer thickness of metallization is normally in the range of 1-10 μm in order to obtain adequate conductivity. Conductive pastes have high metal content (50-90 wt%) [54] and high viscosity (> 200 mPas). The surface tension is required to be within 25-35 mN/m in order to wet the metallization ink on the surface of the anode, cathode and front side barrier. The target for the conductivity for printed metallization structures is to reach the same conductivity values as with the bulk metals. The metallization needs to align with the anode and cathode structures which set requirements for the registration and resolution. The basic properties and targets of the contact pads/bus bars are presented in Table 23.

Table 23. Basic properties and requirements of the contact pads/bus bars.

Properties	Value	Target	Unit
Solids content	50-90	50-70	wt-%
Viscosity	> 5	> 200	mPa·s
Surface tension	25-35		mN/m
Thickness	1-10	~ 1	μm
Roughness	1	< 0.1	μm
Resistance	> 2.8 (Ag)	Min.	$\mu\Omega\text{cm}$
Register	Depends on the module design	100-200	μm

Suitable deposition and drying methods

Suitable processing methods for metallization layer are rotary screen printing, ink jet printing, gravure printing and flexography printing. A thick metallization layer is needed in order to obtain high conductivity for the printed structures. High solid content and high viscosity inks are normally used for preparing metallization. Therefore, the most suitable method for processing the metallization is rotary screen printing. However, screen printing is limited due to line resolution, speed and cost. If finer metallization structures are needed, ink jet printing, gravure printing and flexography printing can be used instead. These printing techniques require lower viscosities than screen printing, however, the solid content can be still relatively high (50-60 wt%). Therefore, several layers need to be printed on top of each other in order to obtain high conductivity.

Table 24. The advantages and disadvantages of suitable deposition methods.

Printing method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - High resolution - High printing speed 	<ul style="list-style-type: none"> - Thin layer - Low viscosity
Inkjet		
Gravure		
Screen printing	<ul style="list-style-type: none"> - High solids content - Thick layer - High viscosity - Low pressure 	<ul style="list-style-type: none"> - Screen blocking - Low resolution

Production process challenges

Conductivity is one of main properties of the metallization. The thickness and conductivity of the metallization are parameters that are highly dependent of each other: For high conductivity, a rather thick metallization layer is needed. A metal layer can be oxidised easily that deteriorates the conductivity of the printed layer. Thicker metallization layer inhibits oxidization and maintains the conductivity of the metallization. However, sintering process of thick metallization layer with relatively low sintering temperatures might cause problems.

Inks for the metallization compose normally of metal particles, solvents, binders and additives. Toxic, non-polar solvents are used as a basis for the metallization ink system. Therefore, material and ink development is needed in order to replace these harmful solvents. The solvents, binders and additives should be chosen in order to take into account the layers processed beneath. The metallization should not dissolve the layers prepared earlier in the OPV manufacturing process. The ink properties in terms of viscosity, surface tension plays a key role in printing of high conductive metallization. The printing method for the metallization structure is chosen according to the requirements for conductivity, layer thickness and homogeneity. The metallization layer is processed on top of cathode, anode and front side barrier layers, so the ink of the metallization layer needs to wet on these different surfaces. The properties of the printing ink and printing method are strongly related to the morphology of the metallization layer and surface topography. Low surface roughness and cleanness are required since they have an impact on the proper adhesion of metallization ink on anode, cathode and front barrier surfaces. The stability of cathode has a moderate impact on the contact pad printing. If the surface energy of the cathode layer changes for instance due to the oxidation, it affects negatively the printing of metallization. The properties of the metallization layer in terms of surface roughness, surface energy have an effect on printing of adhesive layer.

The thermal properties of the plastic foil and organic materials limit the curing temperature of the metallization. Curing temperatures vary between 80°C to 200°C depending on the material choices. Curing temperature and time are strongly related to the conductivity of the metallization. Metal particles need to be coalesced in order to obtain homogeneous layer with high conductivity and low surface roughness. In addition, the ink properties including solvent(s), binders etc. impact on the choice of the curing temperature and time. Furthermore, too thick metallization layer prevents the complete sintering process and thus lower conductivity values are reached. A high thickness of metallization (1-10 μm) increases significantly the total active layer thickness and has a minor impact also on the total thickness of the OPV component. In addition, the thickness of the metallization has an effect on roll-to-roll processability. The conductivity and layer thickness of the metallization are strongly related to OPV shelf lifetime and OPV operating lifetime. Other parameters such as surface topography and cleanness slightly affect the OPV operating and shelf lifetime. Instead, the impact of surface properties in terms of surface energy, surface topography and cleanness

impact moderately on cell efficiency. Since metallization is used for connecting separated solar cells or solar cell modules to other components, the conductivity has a strong influence on monolithic cell integration.

Table25. Challenges and solutions.

Challenges	Solutions
<ul style="list-style-type: none"> - Low surface roughness, homogeneous layer → high conductivity - Toxic solvents - Rather thick layer - Sintering in rather low temperatures → high conductivity 	<ul style="list-style-type: none"> - Optimisation of ink properties, printing and drying process - Material and ink development - Ink formulation + printing process - Optimized sintering and printing process, alternatives for sintering process

3.3.2.8 Adhesive printing and lamination

Layer materials and properties

The organic solar cell needs to be protected against oxygen and moisture in order to maximize and stabilize the OSC lifetime. [28,32,55-63] This results from the easy destruction or oxidation of the cathode and active material upon exposure to these gases. The backside encapsulation is done by applying some adhesive onto the OSC and then laminating the OSC with a plastic film containing a barrier layer. Alternatively, the barrier film can be a tape-like film. The adhesive attaches the OSC to the barrier film and also acts as a sealant. Due to the strict barrier requirements, the adhesive deposition and lamination processes are often done at inert atmosphere.

The adhesive should be solvent-free and fast-curing and have low curing temperature to avoid any damages to the OSC. [28,32,55-63] Therefore, UV-curable epoxy or acrylate resins having 100 % solids content are commonly used. Epoxies have excellent barrier properties and they are commercially available for printing. The viscosity is typically above 100 mPa·s and WVTR and OTR values 0.006 g/m²/day and below 0.01 cm³/m²/day, respectively. However, the better the barrier properties, the more rigid the layer is, thus making R2R processing and adhesion problematic. Acrylates, for their part, are more easily formulated but can be too acidic to the cathode. The adhesive properties can also be changed by adding solvents (e.g. ethanol or acetates) or fillers but they can easily deteriorate the OSC performance or barrier properties. However, it should be noted that the UV-light can seriously damage the photoactive layer. Thus, other types of materials have to be developed when producing high barrier properties. The properties and future targets of the adhesive layer are presented in Table 26.

Table26. Properties and requirements of the adhesive layer.

	Value	Target	Unit
Solids content	Depends on the adhesive		wt-%
Viscosity	> 100		mPa·s
Surface tension	Depends on the adhesive		mN/m
Thickness	2-20	> 1	µm
Roughness	< 1000	< 100	nm
Resolution	Depends on the OSC size		µm
Register	Depends on the module design	100-200	µm

The adhesive layer is typically patterned on top of the OSC but it can also be deposited as a continuous film. [28,32,55-63] The resolution depends on the active area of the OSC and the layer should be 2-20 μm thick to be able to seal the OSC and to attach the barrier film firmly over the whole OSC area. The layer should also be smooth and homogeneous to avoid any sealing problems.

The barrier film that is laminated on the top of the OSC by means of the adhesive layer is typically a plastic film coated with a thin layer of metal or barrier materials (see Chapter 3.2.2). [28,32,55-63] Similar properties are required from the barrier film as from the barrier layer deposited first in the OSC process but the film does not need to be transparent. The barrier films are laminated to the OSC in a nip under pressure. The barrier material can either face the OSC component or outside. If a metal film is used and the metal is facing the OSC, the adhesive layer should be deposited as a continuous film to avoid electric current flow from the cathode to the metal barrier. The barrier layer is typically 10-30 μm thick and the substrate roughness and pinholes play a major role in the layer performance.

Suitable deposition and drying methods

The adhesive layer can be patterned using rotary screen printing, gravure, or flexography because of the fact that the layer should be smooth, pinhole-free, and relatively thick. If the adhesive layer is deposited as a continuous film, coating methods would be the most appropriate since they can produce rather uniform, homogeneous, smooth, and thick layers. Table 27 compares the different deposition methods.

Gravure produces high print resolution at high printing speed. The transferred ink amount can be adjusted by changing the cell volume of the printing cylinder. The printing cylinder has also excellent chemical resistance, thus making gravure suitable for the deposition of UV-curable materials. On the other hand, the gravure ink viscosity has to be rather low to enable ink spreading into solid areas and proper ink transfer. This can lead to too thin layers. In addition, all of the cells do not always transfer ink which forms pinholes. The nip pressure is also rather high which increases the probability for the OSC damage.

The ink transfer amount is easily and accurately adjusted and controlled in the case of flexography. The printing plates are cheap but their chemical resistance is often poor, thus making the use of UV-curable material difficult. However, the low nip pressure of flexography ensures that little damage is caused to the OSC. The resolution and register are poorer than in gravure but this is not an issue unless extremely small cells are produced. Flexography uses also low viscosity inks that produce thin layer onto the substrate.

Screen printing produces thick layer using low printing pressure and high solids content and viscosity inks. Therefore, this method would be the most suitable for the adhesive deposition. The ink layer thickness is also rather easily adjusted. On the other hand, the resolution might be too low in the case of small OSC and the chemical resistance of the screen might also cause problems.

Table 27. Advantages and disadvantages of suitable deposition methods.

Printing method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - Low nip pressure - Accurate and adjustable ink transfer - Cheap printing plates 	<ul style="list-style-type: none"> - Poor resolution - Poor chemical resistance - Low ink viscosity and thin layer
Gravure	<ul style="list-style-type: none"> - High resolution - High printing speed - Superior chemical resistance - Adjustable ink transfer 	<ul style="list-style-type: none"> - Low ink viscosity and thin layer - High nip pressure - Solid tones reproduced via ink spreading - Ink transfer problems
Screen printing	<ul style="list-style-type: none"> - Thick layer - Low printing pressure - High solids content and viscosity 	<ul style="list-style-type: none"> - Poor resolution - Chemical resistance - Low speed
Coating	<ul style="list-style-type: none"> - Thick layer - Smooth and homogeneous layer 	<ul style="list-style-type: none"> - No patterning

The lamination is mainly done by laminating the OSC to barrier film in a nip between two rollers. These rollers are not heated to avoid damage to the OSC but the nip pressure as well as the roller material can be changed to ensure proper contact and adhesion between the two web materials. The UV drying of the adhesive can cause damage to the photoactive layer as a result of which drying at ambient conditions would be preferred but currently the best adhesive materials (high barrier properties) are UV-curable because of the high solids content and viscosity as well as the low spreading ability.

Production process challenges

The WVTR and OTR values of the adhesive and laminated barrier layer have a significant effect on the efficiency, lifetime, and encapsulation of the organic solar cell module. Moisture and oxygen can destroy or oxidise the cathode and active layers of the OSC, thus decreasing both lifetime and efficiency. The main challenge is to find appropriate materials having high moisture and oxygen barrier but still to be flexible enough to enable R2R processing.

The thickness of the adhesive layer is often high to achieve high lifetime and proper encapsulation by preventing oxygen and moisture diffusion into the OSC structure. Thick layers can, however, cause problems in the R2R processing if the adhesive material cracks or is too rigid. The relatively high thickness as compared to the active layers of the OSC affects the total thickness of the OSC.

The adhesive material should be stable and adhere properly onto the OSC to allow proper encapsulation and high lifetime. If the adhesive layer detaches from the OSC or does not withstand the mechanical, thermal, or chemical stresses encountered, oxygen and moisture get into contact with the OSC layers. The layer stability affects also the R2R processability and mechanical strength of the OSC component. The adhesive should also be chemically compatible with the underlying layers so that they are not dissolved or damaged, thus affecting the barrier properties of the OSC. The ink viscosity is typically chosen according to the deposition method and surface tension according to the surface energy of the underlying layers.

The surface properties of the adhesive layer have a significant effect on the encapsulation. The layer should be smooth and homogeneous to achieve proper contact

with the OSC and barrier film and to prevent oxygen and moisture penetration into contact with the cathode or active layers of the OSC. Pinholes are extremely detrimental to the encapsulation since they pass oxygen and moisture directly into contact with the OSC layers. Therefore, material and deposition processes require optimization and development.

The lamination process depends on the plastic foil thickness since too thick or thin materials are difficult to be attached without crack or wrinkles. In addition, the adhesive layer properties affect the quality. The surface properties of the contact pads or bus bars affect the deposition of the adhesive. The surface energy should be higher than the surface tension of the adhesive to allow proper wetting and spreading of the adhesive, and the surface should be smooth and clean to form intimate contact between the adhesive and the OSC (proper encapsulation).

The adhesive layer deposition and lamination are extremely important stages in the OSC manufacturing process since the layer properties determine the final efficiency and lifetime of the OSC by preventing oxygen and moisture transportation into the OSC structure. The most important layer properties affecting the OSC performance are the WVTR, OTR, and stability of the adhesive and barrier layer. The main challenges and their solutions are presented in Table 28.

Table 28. Adhesive layer challenges and solutions.

Challenges	Solutions
<ul style="list-style-type: none"> - WVTR and ORT - Layer stability and adhesion - Smooth and homogeneous layer 	<ul style="list-style-type: none"> - Material development and ink formulation - Process optimization

3.4 Conclusions

The key requirements for the organic solar cells in order to reach entry for the energy market are sufficient lifetime, efficiency and production costs. Low production costs can be obtained by manufacturing organic solar cells (OSC) using low-cost roll-to-roll manufacturing techniques. However, the performance and stability of the OSC need to be improved before the market entry. In addition, alternative materials have to be developed in order to maximize the OSC performance.

Within this contribution, the concentration was on mapping out the requirements for the R2R production equipment and defining the key challenges of the roll-to-roll manufacturing process of organic solar cells by using Quality Function Deployment (QFD) as analysis tool. In addition, the requirements for the online measurements during the R2R manufacturing process were identified in QFD analysis that is of importance for controlling the R2R manufacturing process in order to produce high quality organic solar cell components with high yield. However, the more accurate analysis of the requirements for the measurement instruments and automation systems will be performed in Deliverable D1.4, but the key issues will also be discussed in this conclusion.

Organic solar cells have a multilayered structure where electrodes and active layers are deposited onto the substrate. Due to the high sensitivity of the layers to oxygen and moisture, the cells are encapsulated and sealed by means of barrier layers deposited

onto both sides of the OSCs. There are also contact pads/bus bars to obtain contacts. The most important and challenging layers that require significant development work include barrier and electrode layers.

The barrier layers protect the OSC layers from oxygen and moisture extremely well, thus maximizing and maintaining the cell lifetime and efficiency. However, the barrier properties (WVTR, OTR) are still rather poor as a result of which further material, deposition method, and layer structure developments are required. In addition, the transparency requirement of the front side barrier layer limits the material choice and impairs the barrier properties. The barrier layer should be homogeneous since any cracks or pinholes create a path to moisture and oxygen into the OSC structure. An additional challenge arises from the fact that the substrate onto which the barrier layer is deposited should be clean and smooth so that defect-free and homogeneous barrier layer is obtained. The non-vacuum R2R deposition makes also the achievement of the barrier properties challenging.

The backside encapsulation is a simpler process since the barrier film is laminated by means of adhesive and non-transparent materials (metals) can be used. However, the adhesive layer should also be able to seal the OSC due to which the adhesive layer has to be smooth, flexible, and homogeneous and have proper adhesion.

The electrodes should be highly conductive to obtain high lifetime and efficiency of the OSC. Therefore, the electrode layers should be smooth, homogeneous, and stable. Electrodes might also require inert atmosphere processing, since they oxidise easily, thus diminishing conductivity. This places great demands for the R2R processing. The anode should also be transparent and have excellent resolution as well as sharp edges. The transparency and conductivity requirements require still material and process developments since highly conductive but non-transparent metals cannot be used. The cathode layer should be rather thick in order to protect the active layer from oxidation. Cathode inks are still under development since the lower work function of aluminium would be a more preferable choice than silver and commercial aluminium inks are not available. The final morphology of the cathode is determined in the sintering stage, thus making the sintering stage highly important. A thin electron transport layer might also be required under the cathode.

The measurement needs for the R2R manufacturing process of OSCs can be basically divided into four categories: printing environment measurements, printing machine measurements, measurements for the characteristics of printing inks, printing surfaces and print quality of single layers and OSC component/module measurements. In addition to the actual measurement processes, there is a need for a feedback loop back to the control and adjustment units in order to control the manufacturing process if deviations in the parameters defined in quality definitions are observed. Printing environment measurements compose of measurements for defining the particle level and distribution, temperature, humidity of the printing hall which are of importance in manufacturing functional organic solar cells. Printing machine measurements determine the printing parameters such as printing speed, nip pressure, registration etc. Registration accuracy measurement and recognition is one of the key challenges in the OSC manufacturing process since the single layers need to be aligned with each other in order to produce complex solar cell structures. Misalignment due to the inaccurate registration could lead to the total module malfunction. Especially, transparent layers such as anode and hole injection layers sets challenges for the recognition and thus to the registration with the next layer. In the first phase, the development for the measurement technologies should be concentrated on the characteristics of the printing inks, surfaces and print quality in terms of viscosity, solid content, surface tension, surface energy, layer thickness, density, coverage, spreading, number of pinholes,

uniformity etc. Although, these measurements are indirect, they correlate with the OSC performance, are rather readily available techniques, and are easy-to-install into R2R printing presses. In addition, there is also a need for the online conductivity measurement and measurements for front side and backside barrier properties (defects, VWTR, OTR) since these parameters determine the OSC efficiency and lifetime to a great extent. However, the development of the online measurement methods for the barrier properties is a long term objective, since accurate offline measurements are still under construction. Furthermore, the functionality of OSC component/module according to the quality requirements should be analysed and monitored before and after the lamination process.

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4 Printed displays

4.1 Abstract

Title PRODI WP1 printed display manufacturing requirements

Technical Note ID acr027832

Author(s) L-O. Hennerdal, S. Svensson

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Abstract:

Printed displays are made with a number of technologies such as thermo chromic, electrochromic, electrophoretic, electroluminescent or organic light emitting displays. The most mature is thermo chromic displays and the most demanding technology is the OLEDs.

The technology examined more in detail in this report is an electrochromic display. An EC display is monochrome and easy to print in roll to roll fashion at high speed. The EC display make use of the change in light absorption in PEDOT:PSS when changed from oxidized to reduced state. An EC display can be built either as a lateral structure with the electrodes side by side or as a vertical structure with the electrodes on top of each other. The first generation of EC displays are element based with a predefined image determined before printing. The second generation of EC displays is pixel based and able to show any monochrome image.

The application chosen is a display on a medical package. Other examples of applications for EC displays are greeting cards, indicators, games consumer packaged good etc. The most simple component structure for the first generation of EC displays is the lateral structure. This display can be achieved by a few extra printing steps in a manufacturing line for a medical package.

For the first generation of EC displays screen printing is the state of the art manufacturing process. These displays are laterally designed and printed with a minimum pitch and line width of 100 to 200 μm . Hot air curing and UV curing are used to dry the printed inks. The drying times for the water based inks can be up to 2 minutes thereby affecting the possible printing speed.

The second generation pixel based EC displays make use of inkjet to get narrow line widths and better resolution. The target line widths is 10 to 50 μm and the registration between layers must be better than $\pm 5 \mu\text{m}$. Curing times must be lower than 3 seconds for water based inks and the conductivity in conducting lines less than 10 Ω/\square . To summarize, screen printing is state of the art and preferred production method for the first generation of printed EC displays. For the second generation EC displays ink

jet is the preferred process with the benefits low material waste high flexibility and possibility to print narrow lines.

4.2 Printed displays technology overview

4.2.1 State of the art

Printed displays are not made with one technology but with many, all with different characteristics, and their specific benefits and disadvantages. Whereas older and more mature display technologies commonly are produced in batch processes the printed display technologies promise faster and cheaper production in reel to reel processes. Generally, displays are used in very diverse applications and the requirements on them range from being small and monochrome to being large and multi coloured. Different display technologies address different requirements. Printed display technologies include amongst others thermo chromic, electrochromic, electrophoretic, electroluminescent and OLED technology.

A thermochromic display is built as a laminate or printed image that changes colour with temperature. The temperature is changed by a printed resistor that heats the graphic and reveals a symbol or a word. Thermochromic displays are power hungry because of the relatively high amount of energy it takes to drive the resistors heating the display area. The displays are often simple in design but cheap and environmentally friendly.

Electrochromical displays are built in a different manner. Electrochromism denotes the characteristic colour change of a material associated with the material's reduction-oxidation state. The most employed electroactive material is PEDOT:PSS. Other electrochromic materials are available both commercially and on research levels, but PEDOT:PSS is so far the most suitable since PEDOT:PSS retains a certain level of conductivity also in the reduced state which means that it is not necessary with any additional conductor layers. Oxidation of PEDOT:PSS results in an absorption spectra in the near infra red region due to more free charge carriers, i.e. bi-polarons, and the initial sky-blue coloured polymer turns to a more transparent state. Upon reduction, on the other hand, PEDOT:PSS absorbs strongly in the red/orange wavelength region and appears dark blue to the human eye.

The electrochromic display element can be structured as a lateral electrochemical cell with a pixel electrode and a counter electrode, both covered with a solid electrolyte. The electrodes, which are made from PEDOT-PSS, serve both as electrochromic material and electrical conductor. When a voltage is applied over the electrodes, a redox reaction occurs, in which the reduced electrode becomes dark blue, while the oxidized electrode brightens. The viewing angle is large, weight and cost are low. Energy is mainly consumed when the display is switched. The required voltage is low – typically 1-3 V – which allows for standard battery operation. Keeping the display updated only takes a small sustain current. The display is flexible and it can be folded without damage.

An electrophoretic display forms visible images by rearranging charged pigment particles using an applied electric field. Power is needed to change the image which is created by coloured or black and white particles moving to the front or the back of the display in a viscous medium. The use of microcapsules allows the electrophoretic display to be in the form of a printed active matrix with printed low power transistor

arrays on the back to drive the individual matrix elements. Overall power consumption is very low because of the non volatile characteristic of the technology but printed batteries are not able to power the displays since a relatively high voltage is required.

Electroluminescent Displays are created by sandwiching a layer of electroluminescent material between two layers of conductors. Electroluminescence is an optical and electrical phenomenon where a material emits light in response to an electric current passed through it. When current flows, the layer of material emits radiation in the form of visible light. AC electroluminescent displays have a limited life length and choice of colours and require an inconveniently high driving voltage. Common driving requirements are 50-150 volts at 300 Hz. Electroluminescent displays are mostly used in larger installations as advertisements posters or as replacement of back lit fluorescent light displays. The colours are mainly varied by adding filters, though this reduces the light emitted. Smaller displays are used in mobile phone keyboards, television controllers and even watches. Though high voltages are required the power provided by button batteries is sufficient for these smaller displays.

OLED displays are built using organic light emitting diodes, a light emitting diode whose emissive electroluminescent layer is a film of organic compounds. Beneath the emissive layer of the display there is a conducting polymer. The organic compounds are deposited in rows and columns onto a flat carrier by a simple "printing" process. The resulting matrix of pixels can emit light of different colours. A significant benefit of OLED displays over traditional liquid crystal displays (LCDs) is that OLEDs do not require a backlight to function. Thus they draw far less power and, when powered from a battery, can operate longer on the same charge. Because there is no need for a backlight, an OLED display can be much thinner than an LCD panel.

Lifetime is similar to ac electroluminescent displays at 1000 to 5,000 hours depending on duty cycle, so neither OLED nor ac electroluminescent displays are yet suitable for the 5 year/30,000 hour life demanded now by the automotive industry, the military and others. In spring 2007 Add-Vision demonstrated a first fully printed Organic Light Emitting Diode (P-OLED) device that exceeded 1,000 hours of operating lifetime at peak luminance of 100cd/m^2 . The P-OLED devices were screen-printed under ambient conditions onto thin flexible substrates.

Of the processes developed for printing of the different technologies described above, the printing of thermochromic displays is the process most mature. For flexible OLEDs, both as lighting and as displays, ink jet printing is the most popular route being explored. The requirements on the printing processes are discussed more in detail in the next parts.

The example examined more in detail is a simple **electrochromic display** on a medical package. In such an application customers requirements include good shelf life and disposability but also the contrast and the display power consumption are significant characteristics. For the printed display, these requirements, power consumption and decomposability; translate to the characteristics of the electrodes and electrolyte (high conductivity, redox stability, ion mobility) and to the total mass and hence the thickness of the substrate (weight). The technical requirements also translate into requirements on the equipment used, requirements such as Inkjet nozzle aperture (for inkjet) and Screen mesh count (for screen printing).

Basically a display can be built in either one out of the two following ways; as a simple element based display able to display one predefined message or as a more advanced pixelated display with the ability to show different messages depending on what pixels are lit. In the following sections these different designs are distinguished as a first generation display already today possible to print in a roll to roll production and as a second generation display with tougher requirements on the production process. The technical requirements derived from the customer requirements are separated as current, state of the art values for the first generation displays, and as target values for the second generation displays.

4.2.2 Applications

Being monochrome and element based rather than pixel based the first generation of EC displays is feasible for simple indicator functions or showing line art images or segmented images such as 7 segment digits. Examples of applications in this area are listed below.

Table 1. Examples of EC display applications.

Application	Functions and drivers
Greeting cards	Eye catching effects, highlighting of symbols etc.
Indicators on RFID tags	Semi active and semi passive RFID. Needs and drivers: lower cost, smaller size, better human interface.
Healthcare packaging including medical testers and other disposables	Semi passive time temperature indicators, improved human interface, compliance monitoring packs, disposable testers etc. Needs and drivers: safety, security, convenience, error prevention.
Merchandising novel features	E.g. touch here and it will say what prize you have won. Needs and drivers: Low cost and not bulky. Unique, eye catching.
Games and novelties	Interactive features in disposable products. Need and drivers: Low cost and not bulky. Eye catching.
Leisure, sports	Interactive features in disposable products. Needs and drivers: Low cost and not bulky. Unique, eye catching.
Consumer packaged goods	Interactive features in disposable products. Needs and drivers: Low cost and not bulky. Unique, eye catching.
Small area displays	Eye catching posters, giving illusion of slow movement Needs and drivers: Cost, ease of installation, better human interface.

4.2.3 Component structure

The electrolyte based EC display is monochrome and makes use of the colour change that the conducting Polymer PEDOT:PSS shows at different oxidation/reduction state. In the reduced state the PEDOT:PSS turns to a dark blue colour and at the oxidized state it is very light blue or transparent. The display is consisting of two electrodes where usually one is the actual pixel element and the other electrode is working as counter electrode. To trigger the colour change ion or charge transport is used. This is realized by the help of a transparent electrolyte that covers the electrode and the counter electrode bridging the electrical break in the component. When a potential is applied over the electrodes it starts an ion transport through the electrolyte over the electrical break thereby reducing the display element and oxidizing the counter electrode. Once

switched the display have a certain retention time during which it stays in the switched mode without energy consumption. By changing the polarity the display is deactivated. From a production point of view the simplest layout is to locate the two electrodes side by side in a lateral way. It is also possible to stack the two electrodes on top of each other with the in this case white, litho reflecting electrolyte in between. The components in a EC display are the electrodes consisting of PEDOT:PSS, the electrolyte and the encapsulation. All components are printable; the electrodes are typically a few microns thick while the electrolyte is tens of microns in height.

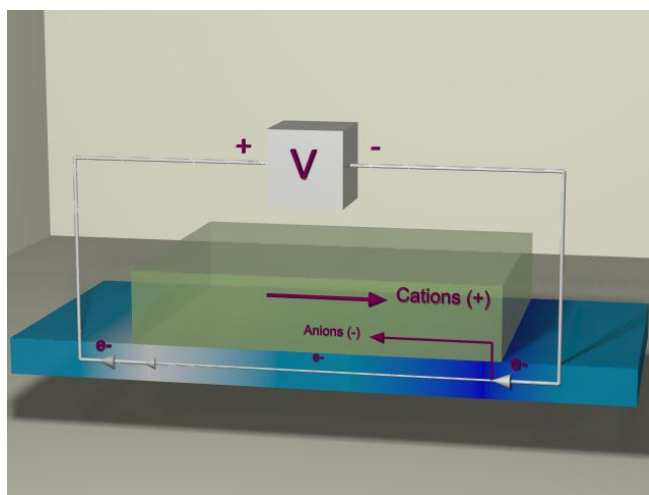


Figure 1. Ion transport in an EC display.

First generation element based lateral printed EC display. The first generation EC displays are element based; they can highlight a symbol, logotype or “static” text that is designed when manufacturing them. The simplest way to print them is the lateral design which is shown below. Screen printing is the preferred printing method to create them from production point of view.

Second generation pixel based vertical printed display. To be able to show whatever monochrome image and to be able to switch between different images or texts you need pixel based displays. These displays have to be driven by multiplexers or decoders. They are also dependent of a (printed) transistor for each pixel. (Figure 2.) This calls for line widths and resolution that is difficult to achieve by screen printing. A high fill factor demands a different construction method than for the first generation displays. Instead of placing layers beside layers in a lateral structure the layers in the second generation display are placed on top each other making it a vertical structure. To make a pixel based display with 90% fill factor and a resolution of modest 25 dpi 100 μ m is left between the rows of pixels to print conducting lines and transistors.

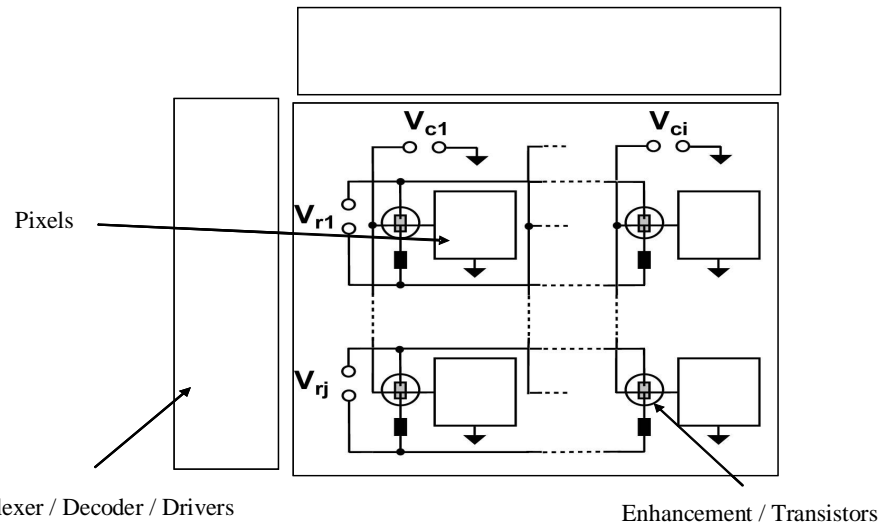


Figure 2. Schematic view over pixel display with enhancement transistors on each pixel.

4.2.4 Manufacturing process description

Making a first generation lateral display first the two electrodes are screen printed side by side using a PEDOT:PSS ink. The printed layer thickness is $\leq 10 \mu\text{m}$. In the simplest design PEDOT:PSS also can be used as connectors in that case they are printed in the same step as the electrodes. If lower resistance in the connecting lines is wanted they can be printed in carbon or silver as a second step. The electrodes and the connectors are hot air dried. The electrolyte needs to be printed in a thicker layer ($\leq 30 \mu\text{m}$) and is UV cured to form a solid rubber like layer. To even out variations in the influence from air humidity variations and as mechanical protection an encapsulating foil is applied. (Fig. 3.) There is also a subtractive patterning method for the PEDOT:PSS available where the starting point is a globally coated PEDOT:PSS layer on a plastic foil. In this case the patterning of electrodes are made by electrochemical over oxidation while screen printing an electrolyte and applying a potential over the printed area. The electrolyte used for this electrode patterning is cured and deactivated by UV radiation immediately after being printed.

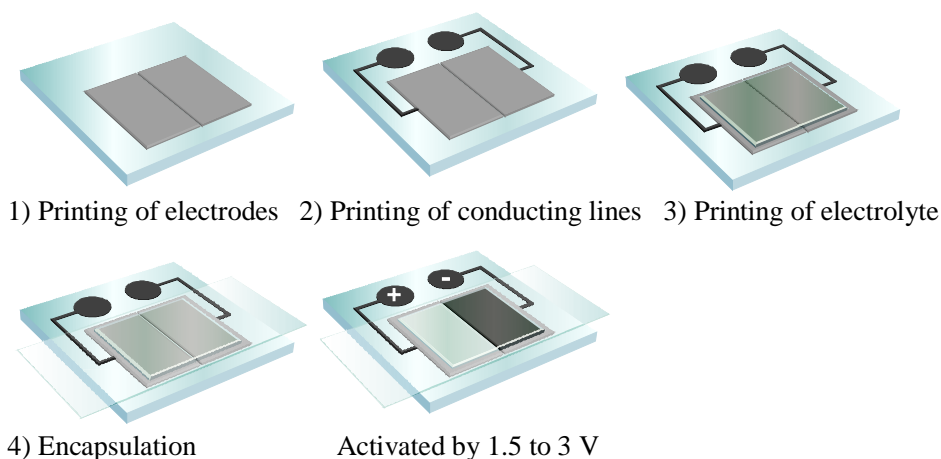


Figure 3. Manufacturing process phases.

If we are to consider the production in the light of the example chosen before, an EC display on a medical package, we would like to use inkjet for the electrodes and conducting lines since it offers a quick and easy road between the digital design and the printing unit. For the electrolyte though we need a thicker layer deposited and we have to use screen printing. The inkjet needs to be enhanced in order to match the speed of R2R printing and the screen printing is required to produce a thick enough layer still having sufficient resolution. Curing speed is crucial in both cases.

4.3 Printed display manufacturing requirements

4.3.1 Technological requirements and challenges

Requirements on first generation element based lateral displays. Screen printing is the method used for the first generation of EC displays; mainly because the method is relatively straightforward and can be used both in roll to roll production as well as sheet (flat screen) production. Typical minimum line width and pitch for screen printing is 100 to 200 μm . Hot air curing is used for the PEDOT:PSS and the conducting lines. Typical drying temperature is 120 $^{\circ}\text{C}$ during less than 2 minutes. The screen printed electrolyte is UV cured to a semi solid rubber like consistence. Total thickness without substrate is typically 40 μm . A variety of substrates can be used from paper to different plastic foils. Production can be utilized in normal clean industry environment, conventional clean room is not necessary.

Requirements on second generation pixel based vertical displays. The demands for narrow line width and high resolution as well as accurate registration between layers in the second generation of EC displays are significantly raised. A line width of less than 50 μm and preferably down to 10 μm is necessary. Rapid thermal curing or UV curing is also preferred. To obtain low resistance in conductive lines and layers ink development as well as process development is needed. Even if advanced screen printing can produce line widths well below 50 μm ink jet printing is the preferred method. Ink jet has the advantage of direct digital steering without the need for special printing forms such as screens etc. It is feasible for printing single items or small series and it is also possible to personalize the printing thereby making every printed item unique. Ink jet printing can be utilized sheet by sheet or continuous roll to roll.

Typical process parameters are line widths between 10 to 50 μm , thermal drying time < 3 seconds (20 m/minute web speed and 10 cm between each printing step). Sintering/annealing at low temperature < 120°C creating low resistive conducting lines close to bulk metal. Very good registration between layers, < 5 μm miss alignment, is necessary as well as a total thickness without substrate less than 10 μm .

4.3.2 Production process requirements and challenges

4.3.2.1 Substrate pre-treatments and converting

The thickness of the substrate should be as small as possible to minimize the environmental impact and increase the flexibility of the display. As a beneficial side effect low thickness should lower the cost of the substrate.

Generally one would like the same surface energy for the substrate as for the ink but it is also possible to use a difference in surface energy between the materials to get a specific behaviour. By using a substrate with less surface energy than the surface energy of the ink one can achieve more narrow lines. The difference helps the ink not to spread on the substrate and to stay put where it is applied.

A paper substrate can be used but then it should be coated in order for the substrate not to absorb the liquid content of the inks. Absorption can cause unwanted electrical effects and also the appearance of the display is affected.

Table 2. Basic properties of plastic substrates.

Properties	Value	Target	Unit
Thickness	< 100	<36	μm
Roughness, R_a	< 50 ^[1]	< 20	nm
Surface energy	20-50	> 50	mN/m
Transmission	> 80	> 90	%
Max. temperature	< 200		°C

4.3.2.2 Electrode printing and curing

Layer materials and properties

A higher solid content in the PEDOT:PSS based ink should give a shorter drying time and a higher conductivity. In turn the higher conductivity will allow for printing thinner layers and other printing methods like flexo. If the layer thickness is minimized then cost will go down. Resolution is important in order to minimize feature size.

The sensitivity to variations in the surface, i.e. roughness is not as high for displays as for many other applications like solar cells. On the other hand roughness influence how thin layers can be because a too high value can cause short circuit between layers. Inkjet printing requires a lower viscosity and therefore the target is to minimize this value.

Table 3. Properties and requirements for the conductive inks.

Properties	Value	Target	Unit
Solids content	2	20	wt-%
Viscosity	60-100 ^[2]	<10	mPa·s
Surface tension	71 at 20 °C ^[3]	71	mN/m
Thickness	≤5	≤2	μm
Roughness	> 1	< 0,5	μm
Resistance	1	< 0. 5	kΩ/sq
Resolution	80-200	10	μm

Suitable deposition and drying methods

In the first generation of printed displays screen printing is state of the art, it is a simple and straight forward method and yet possible to run in roll to roll production. It is also possible to deposit the thick layer of electrolyte that is needed in a simple way. In the second generation of displays ink jet printing is preferred as it is more digital, contactless and suitable for small feature size. Since it is not yet a mature method much development of performance is to be expected. Rapid curing of the printed inks is crucial for roll to roll production. UV curing gives an almost instant curing and offers possibilities for fast roll to roll production. Unfortunately it is not suitable for printed conductors such as PEDOT:PSS, carbon and silver because the UV cured inks are not volatile and leaves the base or vehicle of the ink more or less unaffected thereby preventing a good contact between the conductive elements (or particles) in the ink. Due to the bad contacting of UV cured inks ink producers are for the time being left with the option to develop inks suitable for hot air curing bearing in mind that short curing time is an essential characteristic.

Table 4. Advantages and disadvantages of the potential deposition methods for conductive polymer layers.

Method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - Thin layer - Low viscosity inks - Low nip pressure - Adjustable ink transfer 	<ul style="list-style-type: none"> - Poor resolution and register - Excessive spreading
Gravure	<ul style="list-style-type: none"> - Thin layer - Low viscosity inks - High resolution - Adjustable ink transfer 	<ul style="list-style-type: none"> - Solid tones reproduced via ink spreading - Ink transfer problems - Excessive spreading - High nip pressure
Offset	<ul style="list-style-type: none"> - Thin layer - No excessive spreading - High resolution 	<ul style="list-style-type: none"> - High viscosity inks - Ink layer roughness - High nip pressure
Inkjet	<ul style="list-style-type: none"> - Thin layer - Low viscosity inks - High resolution - Non-contact 	<ul style="list-style-type: none"> - Low speed - Nozzle clogging - Excessive spreading
Screen printing	<ul style="list-style-type: none"> - Commercially available inks - Low pressure - Thick layers → covers roughness 	<ul style="list-style-type: none"> - High viscosity inks - Thick layers - Poor resolution

Production process challenges

To get a sufficiently high conductivity we want a higher solid content in the conducting ink, in particular in PEDOT:PSS, which allows us to print thinner layer still with good conductivity. Curing annealing must be possible at low temperature ($< 120\text{ }^{\circ}\text{C}$) and be applied during short time, a few seconds in roll to roll printing. Good conductivity is dependent on the annealing/sintering to let the conductive particles in the ink form a good and homogeny conductive strip. The first generation displays will use screen printing for the conductors, second generation probably ink jet printing. In both cases ink development in to achieve shorter drying times is needed.

Table 5. Challenges of the electrode layer and the solutions.

Challenges	Solutions
<ul style="list-style-type: none"> - Low conductivity - Layer homogeneity and roughness - Thickness and resolution requirements 	<ul style="list-style-type: none"> - Printing process optimization - Material development and ink formulation

4.3.2.3 Conductors and contact pads printing and curing

Layer materials and properties

When designing and manufacturing a display uniform layer thickness is preferred. This will give the benefit of lower and fewer steps to overcome by conducting lines or encapsulating or insulating layers.

Table 6. Basic properties and requirements of the contact pads/bus bars.

Properties	Value	Target	Unit
Solids content	20	50	wt-%
Viscosity	~100	<10	mPa·s
Surface tension	71	71	mN/m
Thickness	≤ 5	≤ 2	μm
Roughness	> 1	$< 0,5$	μm
Resistance	40-60	< 5	$\mu\Omega\text{cm}$
Register	30	< 5	μm

Suitable deposition and drying methods

UV curing, although allowing for high production speed, is not possible as it prevents good conductivity in the conducting lines. This calls for serious efforts in ink development. Conductive inks available so far are developed for batch production and often demands drying times of 15 minutes or more at relative high temperatures. This is unacceptable in any kind of mass production where short drying times (a few seconds) and low temperatures (below $120\text{ }^{\circ}\text{C}$) is needed.

Table 7. The advantages and disadvantages of suitable deposition methods.

Printing method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - Thin layer - Low viscosity inks - Low nip pressure - Adjustable ink transfer 	<ul style="list-style-type: none"> - Poor resolution and register - Excessive spreading
Gravure	<ul style="list-style-type: none"> - Thin layer - Low viscosity inks - High resolution - Adjustable ink transfer 	<ul style="list-style-type: none"> - Solid tones reproduced via ink spreading - Ink transfer problems - Excessive spreading - High nip pressure
Offset	<ul style="list-style-type: none"> - Thin layer - No excessive spreading - High resolution 	<ul style="list-style-type: none"> - High viscosity inks - Ink layer roughness - High nip pressure
Inkjet	<ul style="list-style-type: none"> - Thin layer - Low viscosity inks - High resolution - Non-contact 	<ul style="list-style-type: none"> - Low speed - Nozzle clogging - Excessive spreading
Screen printing	<ul style="list-style-type: none"> - Commercially available inks - Low pressure - Thick layers → covers roughness 	<ul style="list-style-type: none"> - High viscosity inks - Thick layers - Poor resolution - Screen blocking

Production process challenges

In a first generation, conducting lines of carbon or silver are screen printed and heat cured; in a second generation they are probably ink jet printed, heat cured and annealed.

Table 8. Challenges and solutions.

Challenges	Solutions
<ul style="list-style-type: none"> - Low surface roughness, homogeneous layer -> high conductivity - Toxic solvents - Rather thick layer - Sintering in rather low temperatures -> high conductivity 	<ul style="list-style-type: none"> - Optimisation of ink properties, printing and drying process - Material and ink development - Ink formulation + printing process - Low temperature sintering and printing process, alternatives for sintering process

4.3.2.4 Electrolyte printing and curing

Layer materials and properties

For the electrolyte we want to minimize the solid content as this part of the ink is not electrically active but serving as a vehicle to make the electrolyte printable, curable and mechanically stable. If we can lower the solid content we will be able to print thinner layers, getting faster switch times for the display which in turn will give benefits for economy, environment and flexibility of the component. Low solid content will also give the opportunity to use ink jet rather than screen printing as production method. Low surface roughness will also increase possibilities to use thinner layers without the risk for pinholes or short-circuits. As a beneficial side-effect light transmission through the

electrolyte also get enhanced with thinner printed layers. For second generation of displays ink jet is a preferred method since it offers possibility to print smaller features and better registration between layers.

Table 9. Properties and requirements for the electrolyte layer.

Properties	Value	Target	Unit
Solids content	~70%	50 %	wt-%
Viscosity	60-100	<10	mPa·s
Surface tension	71	71	mN/m
Thickness	30	10	μm
Roughness	5	0,5	μm
Light transmission	> 70	> 90	%
Register	30	< 5	μm

Suitable deposition and drying methods

Today only screen printing is a viable option because it is the only method available that can print a sufficiently thick layer for the ion mobility needed. Screen printing is somewhat slower than other printing methods besides ink-jet.

In a second generation of displays the small feature size and thinner layers make ink jet printing more attractive than screen printing. The electrolyte must still be UV cured which should be considered when designing production equipment.

Table 10. Advantages and disadvantages of the different deposition methods for the display components.

Printing method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - cheap printing plates - low nip pressure - accurate and adjustable ink transfer 	<ul style="list-style-type: none"> - <u>thin layer</u>
Inkjet	<ul style="list-style-type: none"> - non-contact (no pressure) - high quality - 	<ul style="list-style-type: none"> - <u>thin layer</u> - low speed - nozzle clogging
Gravure	<ul style="list-style-type: none"> - high quality - high speed - adjustable ink transfer 	<ul style="list-style-type: none"> - <u>thin layer</u> - expensive printing cylinders - solid tones reproduced via ink spreading - ink transfer problems - high nip pressure
Screen Printing	<ul style="list-style-type: none"> - thick layer - commercially available inks - low pressure 	<ul style="list-style-type: none"> - medium speed

Production process challenges

To develop a printable polymer based dry solid electrolyte possible to use at high resolution displays is certainly a challenge. The electrolyte will be screen printed and UV cured in first generation displays, and probably ink jet printed but still UV cured in a second generation (pixelated) displays.

Table 11. Challenges of the electrolyte layer and the possible solutions to the problems.

Challenges	Solutions
<ul style="list-style-type: none"> - Poor mechanical strength (low adhesion) - Thick layers 	<ul style="list-style-type: none"> - Ink formulation and optimization

4.3.2.5 Encapsulation

Layer materials and properties

Table 12. Properties and requirements of the encapsulation layer.

Properties	Value	Target	Unit
Thickness	20	> 5	μm
Roughness	< 50 ^[1]	< 20	nm
Register	30	5	μm
Water vapour	16 ¹	<3	g/m ² x d

Suitable deposition and drying methods

Table 13. Advantages and disadvantages of suitable deposition methods.

Printing method	Advantages	Disadvantages
Flexography	<ul style="list-style-type: none"> - Low nip pressure - Accurate and adjustable ink transfer - Cheap printing plates 	<ul style="list-style-type: none"> - Poor resolution - Poor chemical resistance - Low ink viscosity and thin layer
Gravure	<ul style="list-style-type: none"> - High resolution - High printing speed - Superior chemical resistance - Adjustable ink transfer 	<ul style="list-style-type: none"> - Low ink viscosity and thin layer - High nip pressure - Solid tones reproduced via ink spreading - Ink transfer problems
Screen printing	<ul style="list-style-type: none"> - Thick layer - Low printing pressure - High solids content and viscosity 	<ul style="list-style-type: none"> - Poor resolution - Chemical resistance - Low speed
Coating	<ul style="list-style-type: none"> - Thick layer - Smooth and homogeneous layer 	<ul style="list-style-type: none"> - No patterning
Lamination	<ul style="list-style-type: none"> - Standard process for roll to roll manufacturing - No step drying needed - High speed 	<ul style="list-style-type: none"> - No patterning

Production process challenges

State of the art for the first generation of displays is laminated encapsulation - one of the main benefits being simplicity. One can plainly use standard lamination steps in the roll to roll machinery. The disadvantage is that it is not possible to pattern the encapsulation which introduces unwanted restrictions in the design rules.

In a second generation of displays printed encapsulation is preferable. This in turn calls for development of (transparent) inks with good barrier properties.

Table 14. Encapsulation layer challenges and solutions.

Challenges	Solutions
<ul style="list-style-type: none"> - Development of printed encapsulation with low permeability 	<ul style="list-style-type: none"> - Material development and ink formulation - Process optimization

4.4 Conclusions

Screen printing is the preferred process and state of the art for the first generation of element based EC displays. The challenges are narrow line widths and narrow pitch but above all drying times for the water based PEDOT:PSS ink. The PEDOT:PSS ink requires a drying time of ≥ 2 minutes in 140 °C air temperature and this demands for long drying sections in roll to roll production or production at very low speed. One way to increase the production speed is to use foils that are pre coated with PEDOT:PSS and use the faster EC patterning method described above to “print” conductors and displays with the drawback that more than necessary of the expensive PEDOT:PSS ink is being used. The main challenge to enhance the process is therefore to reduce the drying time for PEDOT:PSS ink. The table below summarizes what is possible today in a first generation production process.

Table 15. EC display production; first generation values and second generation targets.

EC display production	First generation values	Second generation target
Line width	100 to 200 μm line width.	10 to 50 μm
Resistance in conducting lines and electrodes	$< 500 \Omega/\square$.	$< 10 \Omega/\square$.
Registration	Better than $\pm 50 \mu\text{m}$ between layers.	Better than $\pm 5 \mu\text{m}$ between layers.
Hot air curing	Less than 2 minutes curing time	Hot air curing/annealing less than 3 seconds curing time in roll to toll production.
UV curing	UV curing of electrolyte.	UV curing of electrolyte.
Height	$< 40 \mu\text{m}$ height excluding substrate.	$< 10 \mu\text{m}$ height excluding substrate

For the second generation EC displays ink jet is the preferred process; the benefits of this method being low material waste, high flexibility regarding design and steering of the process and possibility to print narrow lines. The challenges are to achieve short drying/annealing times to allow high printing speeds and the possibility to do roll to roll production. The requirements for second generation displays derived from the discussions in previous chapters are summarized in the table above. Low sintering temperatures $< 120 \text{ }^\circ\text{C}$ for metal inks are also necessary.

Table 16. Future demands and its implication on the process and materials

Future demands	Implications on the process and materials
Rapid drying/curing	Ink development towards faster drying. Process development towards more efficient drying of water based and solvent based inks.
Low sintering/annealing temperatures < 120 °C	Ink development, use of nanoparticles etc.
Solid electrolytes	Development towards thinner electrolyte layers, faster switching times, electrolytes for high respective low retention time, better mechanical properties etc.
Narrow line width < 50 down to 10 μm	Smaller drop size for inkjet, surface energy treatment and modulation/patterning.
High conductivity in leading lines and electrodes.	Low sintering temperature for metal inks. Low annealing temperature for polymer inks.

4.5 Selected publications

- [1] http://www.m-petfilm.com/upload/Europe_104ENG.pdf
- [2] http://www.ampertec.info/index.php?page_id=995&prod_service_id=438
- [3] <http://www.ampertec.info/>

5 OTFT for display

5.1 Abstract

Title PRODI WP1 OTFT for display manufacturing requirements

Technical Note ID TN-07-SIF-TPX-XXX

Author(s) G. Pieterse

Reviewed by P.T.M. Giesen, E.R. Meinders, M. Thornton

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Abstract:

This report describes the results of a literature review carried out for WP1 within the Prodi project. This project addresses the suitability of roll to roll manufacturing methods for the fabrication of organic electronics. Within WP1, our task is to gather information about the short, medium and long term requirements for the fabrication of thin film transistors (OTFTs) for display applications. The report starts with a brief introduction of the organic TFT theory. The application parameters were gathered and the technological parameters were derived by a literature study of more than 130 peer reviewed scientific publications and a quality function deployment (QFD) approach described by our partner in WP1 (VTT). The detailed results of the QFD analysis are available in a separate excel file and are summarized in this report. From the technological parameters, the manufacturing requirements are derived per device feature; i.e. substrate, gate, dielectric, organic semiconductor, source, drain, and some supplemental features. Using the requirements, the appropriate manufacturing techniques are selected. For patterning manufacturing steps, we will focus on 'conventional' printing technologies, i.e. **flexographic, gravure, offset, screen and inkjet** printing. We will evaluate **coating and lamination** for process steps involving uniform layers. Additionally, we will look at **evaporation** processes because it is expected that using standard printing technologies to produce certain features (such as the organic layer) in stead, will not lead to devices with comparable performance, not even on the long term. Finally, we will also look at **soft lithography** as an alternative hybrid patterning technique.

5.2 OTFT for display technology overview

One of the most promising applications for roll-to-roll manufactured organic electronics is display technology. This subject has drawn a lot of attention of existing companies and many start ups. At present, concurrent approaches are followed to meet the demand for flexible displays. The first approach is converting the existing inorganic silicon on wafer technology - such as lithography - to silicon on flexible substrate technology. A second approach is to use organic substances as a replacement functional material, preferably using printing technology for coating and patterning the different parts. The third important approach is to combine the benefits of inorganic and organic technology in so-called hybrid solutions.

We will focus on the driving electronics for flexible display applications, more specifically, the flexible thin film transistors (TFT) that are the most critical part of the driving electronics for displays.

The key potential benefits of converting existing wafer based silicon based solutions for TFT for display technology are the low power consumption and high switching frequencies, and high electrical stability of silicon based technology. The current main drawback of silicon based technology is that existing production equipment does not allow for large volume continuous processing. For this reason, the use of organic materials with existing large volume conventional printing technologies is currently actively investigated. The current drawbacks of using organic materials for the functional materials are the large power consumption, the low switching frequencies, and low electrical stability of these materials.

In the following sections, we will address the use of organic materials for the functional layers to produce organic TFT's (OTFT) using printing technologies. The problems associated with using organic materials for producing OTFT's are threefold. First, the electrical performance of the available organic materials is inferior to the electrical performance of their inorganic counterparts. Much research and development is still required to develop organic material configurations that will have a performance that approaches the performance of inorganic materials. Secondly, a mismatch exists between the conventional printing techniques and the fluidic properties and processing requirements of the available organic materials, making conventional processing of these materials far from straightforward. Finally, because of the limitations in the material properties at present, the actual design parameters and configurations for organic circuitry are dependent on the combination of materials, the printing technology used for the production, and the intended application. An OTFT for display applications will have a completely different layout as an OTFT for radiofrequency identification. It is for this reason the display application of OTFT was chosen for this survey.

5.2.1 State of the art

For a complete overview of the state of the art of flexible display technology, the reader can refer to the 2009 roadmap of the Organic Electronics Association (OE-A), or the 2009 roadmap of the international Electronics Manufacturing Initiative (iNEMI) roadmap. Additional information may also be found via the German Flat Panel Display Forum (DFF).

5.2.2 Applications

The applications for OTFT for display considered in this study were obtained from the OE-A application roadmap for OTFT for displays:

- Short term: Black and white, flexible DIN A5 displays with refresh rates in the order of 1 Hz.
- Medium term: Color, flexible DIN A5 displays with refresh rates in the order of 10 Hz.
- Long term: Full color, flexible large area displays with refresh rates in the order of 100 Hz.

Whereas the OE-A roadmap mainly focuses on the applications of OTFT technology, this research addresses the specific requirements for manufacturing the different parts of an OTFT for display.

5.2.3 Component structure

An OTFT consists of a gate, source and drain contact separated by an insulator and a semiconductor, see Figure 1. It can be used to amplify or switch electric signals by controlling the current between the source and drain with a bias voltage on the gate contact. In the off-state, either for large positive or negative gate bias, the OTFT is non conducting and no current can flow between the source and drain. In the on-state, the current between the source and drain is dependent on the gate bias voltage.

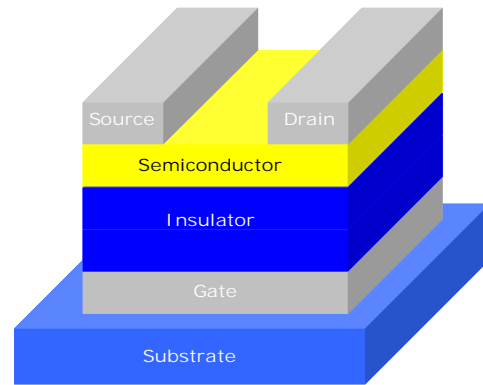


Figure 1. Basic OTFT structure (bottom gate, top contact).

There are four basic different configurations for OTFT, depending on the location of the source, drain and gate with respect to the other layers. The gate can be located either at the bottom of the device (Bottom Gate, BG) or at on top of the device (Top Gate, TG). The source and drain contacts can be located either below the semiconductor layer (Bottom Contact, BC) or on top of the semiconductor layer (Top Contact, TC). These basic configurations are shown schematically in Figure 2.

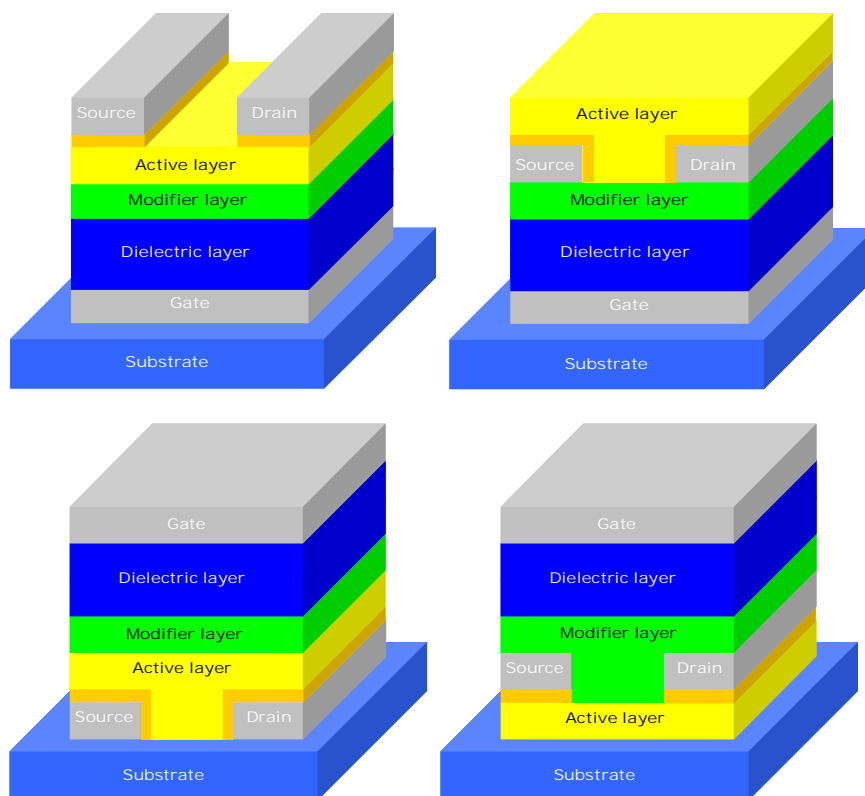


Figure 2. Different OTFT device configurations. (Top-Left) Bottom gate, top contact (Top-Right) Bottom gate, bottom contact (Bottom-Left) Top gate, bottom contact (Bottom-Right) Top gate, top contact.

Each OTFT configuration has its advantages and disadvantages, for manufacturing and for final product performance. The preferred configuration also depends on the application for which the OTFT is used on the design of the application. Objectively, there is no preferred configuration at the moment but scientific literature reports more bottom gate configurations than top gate configurations, and some studies (e.g. Gupta et al., 2009) indicate that the top contact configuration generally show better performance. For this reason we will also look at bottom gate top contact configuration in this study. It is important to note that, although the sequence order will be different and this may cause different manufacturing challenges, the manufacturing techniques presented here are in principle also usable for the other configurations.

Besides the generic features of the OTFT, two additional features are shown in Figure . The first feature (shown in green) is the modifier layer which adapts the chemical and electric properties of the dielectric surface layer to:

- Ensure proper electric properties at the interface between the dielectric and the active layer.
- Enable better control over the manufacturing process of the active layer.

The second feature (shown in orange) is a possible additional dopant layer (n- or p-type) between the source and drain contacts and the active layer. This feature enables the use of ambipolar semiconductors (see e.g. the Novaled technology) as an alternative to polar (n- or p-type) semiconductors.

Depending on the properties of the used materials and the intended performance of an OTFT, different configurations of the source-drain-gate geometry may be preferred. To

understand why this is important some basic knowledge about OTFT operation is required. Two geometric properties are important for optimizing the performance of an OTFT. The most critical property is the distance between the source and the drain, or **channel length** (L) and the second is the **channel width** (W) of the channel between the source and drain, shown in Figure 3.

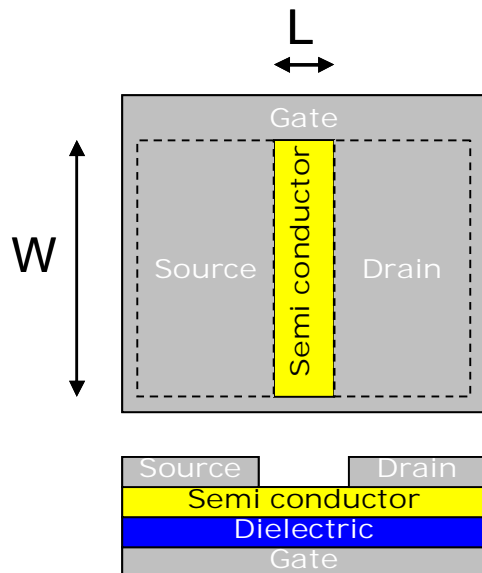


Figure 3. Schematic view of the OTFT channel width (W) and length (L).

Together with the properties of the dielectric and semiconductor, these two geometric parameters determine the typical response of an OTFT, shown in the current-voltage (I-V) diagram in Figure 4.

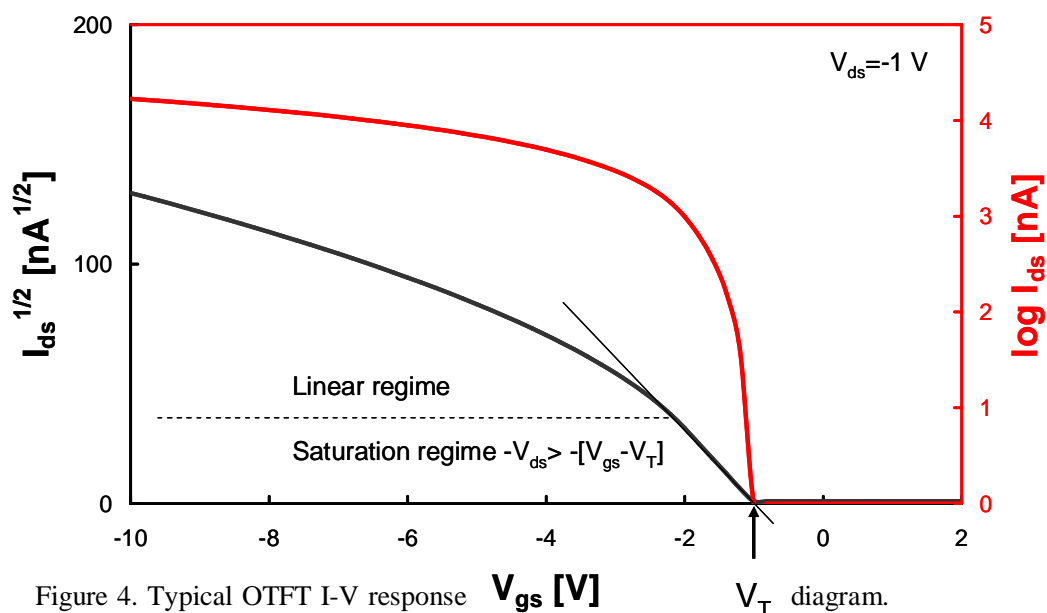
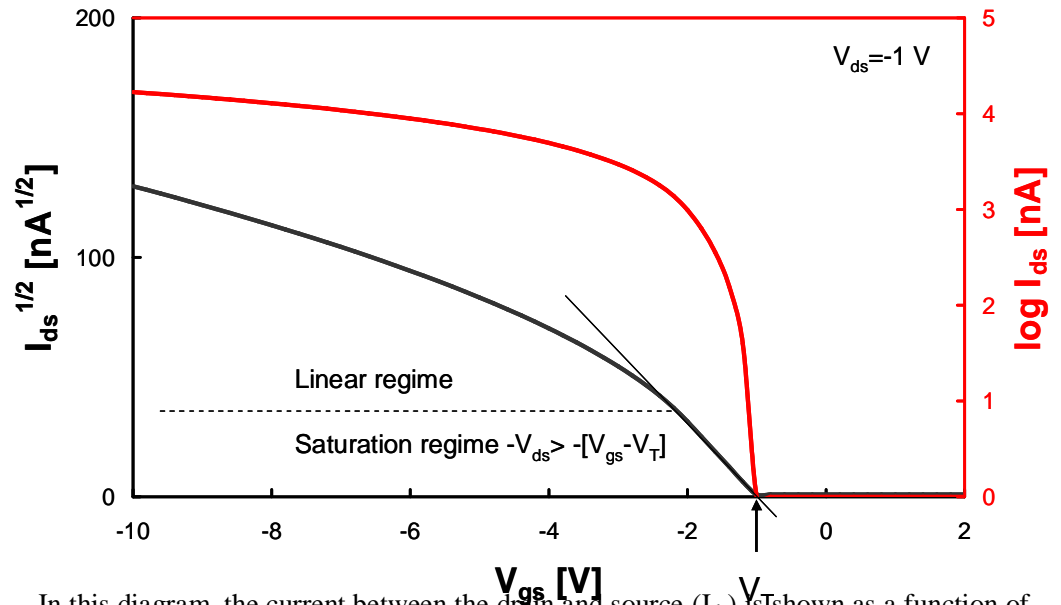


Figure 4. Typical OTFT I-V response V_{gs} [V] V_T diagram.



In this diagram, the current between the drain and source (I_{ds}) is shown as a function of the bias voltage between the gate and the source (V_{gs}). This performance is valid for a fixed bias voltage between the drain and the source (V_{ds}).

Several features of an OTFT can be derived from this diagram. The left vertical axis shows the square root of I_{ds} as a function of V_{ds} . The approximate analytical relation between I_{ds} and V_{gs} in the so-called saturation regime, in this case a small region near the **threshold voltage** (V_T), is:

$$I_{ds} = \frac{W}{2L} \mu C_i (V_{gs} - V_T)^2.$$

Here, μ [$\text{cm}^2/\text{V}\cdot\text{s}$] is the **saturation carrier mobility** and C_i [F/cm^2] is the **capacitance** of the dielectric. The carrier mobility and threshold voltage are two important parameters determining the electric performance of an OTFT. Using the analytical expression, μ and V_T can be inferred from the I-V response diagram using a tangent line construction for the part of the curve that lies in the saturation regime. The capacitance of the dielectric can be calculated using the following expression:

$$C_i = \kappa \frac{\epsilon_0 A}{d},$$

Here, κ is the relative static permittivity of the dielectric, ϵ_0 [F/m] is the permittivity of vacuum, A [m^2] is the effective surface area of overlap between the source and drain contacts and the gate, and d [m] is the thickness of the dielectric. In all, there is a large number of parameters determining the performance of an OTFT. The list of parameters shown here is not exhaustive but provides a good overview of the most important parameters. In the table below, the effect of increasing the values of the different parameters on the on-current $I_{ds(\text{on})}=I_{\text{on}}$ is illustrated (assuming negative V_{gs}):

Table 1 Effect of increasing individual parameters on $I_{ds}(on)$.

Parameter +	$I_{ds}(on)=I_{on}$
W	+
L	-
μ	+
κ	+
A	+
d	-
V_T	+

Another important parameter is the I_{On}/I_{Off} ratio, the ratio between the current I_{ds} in the on-state and in the off-state of the OTFT. It is a measure of how discernable the on- and off-state are. This parameter can be easily derived from the red curve in

Figure 4 by extracting the maximum and minimum current values and taking the ratio. The value of $I_{ds}(off)=I_{off}$ depends on the bias voltage between the source and drain and the conducting properties of the semiconductor when the OTFT is in the off-state.

Hysteresis is a parameter that quantifies the difference in the I-V diagram when going from the off- to on-state and the on- to off-state. (Hwang et al., 2008) have separated hysteresis into three general mechanisms: (1) a channel/dielectric interface induced effect because of charge trapping due to OH groups present at the interface (2) a residual dipole-induced reorientation effect; (3) the effects of charges injected from gate electrode that are trapped in the dielectric. Lowering the activation and deactivation rates of traps will reduce hysteresis.

The final important parameter is the switching **frequency**. It is proportional to μ/L^2 , and this is the reason why many research groups are focusing on maximizing mobility and minimized channel length.

5.2.4 Manufacturing process description

At present, no 'standard' roll-to-roll manufacturing sequence to produce OTFT's exists. This is mainly due to the fact that the current scientific focus is mainly on finding material combinations and processing techniques to optimize basic OTFT performance, which is still inferior to the silicon on wafer technology. Furthermore, the concurrent development of inorganic TFT's on flexible substrates aggravates making strategic decisions on which underlying material technology to choose, organic and/or inorganic, and herewith also the manufacturing techniques to choose. We will limit our focus on the application of organic materials for the semiconducting part of the OTFT. Figure shows a schematic overview of a possible manufacturing sequence for producing a bottom gate-top contact OTFT. In this section, we will give a brief description of the manufacturing sequence. A more detailed description of the individual steps can be found in Chapter 5.3.

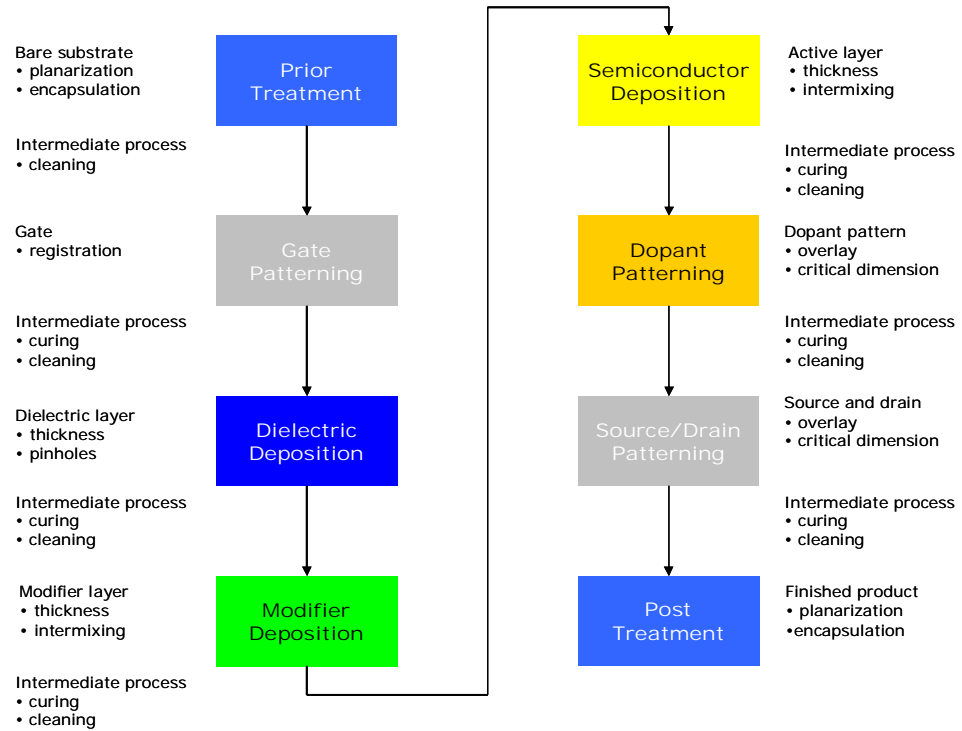


Figure 5 Schematic overview of manufacturing sequence for BG-TC OTFT.

The manufacturing sequence starts with the bare flexible substrate, usually a material like Polyethylene terephthalate (PET), Polyethylene naphthalate (PEN) or polyethersulfone (PES). The surface of the substrate is generally thoroughly cleaned, chemically passivated, and the surface energy is improved using a corona plasma. Because high patterning resolutions are required for the gate, source and drain contacts, and shallow layers are deposited on top of the substrate; the surface roughness of the bare substrate should be minimized to avoid geometric problems. If the surface roughness of the bare substrate is too large for the geometric requirements of the OTFT, a planarization layer can be applied.

In some cases, e.g. when a Mylar® (Du Pont) or polyimide (PI) substrate is used, the substrate is also suitable as gate dielectric. In that case, the gate electrode can be patterned on the backside of the substrate. In other cases, the gate is patterned on top of the substrate. This can be done using many different processes such as (inkjet) printing, photochemical patterning, shadow mask deposition, soft lithography, followed by curing or drying.

After deposition of the gate, the dielectric is deposited. Depending on the material that is used, organic and/or inorganic, the deposition process will typically be a coating or evaporation process followed by curing or drying. In order to optimize the OTFT performance, the surface of the dielectric is frequently modified before application of the semiconductor layer, either by chemically and/or physically altering the surface of the dielectric or by adding a modifier layer. Subsequently, the semiconductor layer is deposited on the dielectric. It is vital to ensure a proper connection between the two layers because the current will flow near the interface between the dielectric and the semiconductor. Any chemical/structural imperfection will cause charge trapping and herewith decrease device performance. Another parameter to optimize is the semiconductor **grain size**. Due to charge trapping at the grain boundaries the resistance between the source and the drain is increased, and therefore it is considered important to optimize grain size, i.e. to reduce the number of grain boundaries between the source

and the drain. Recent studies however suggest that grain size is not the only limiting factor and that molecular organisation within the grain could also be responsible for charge trapping.

After deposition and curing the semiconductor material, the source and drain contacts are deposited. If the used semiconductor is ambipolar, i.e. no preference exists for either electrons or holes as charge carrier, additional dopant patterning between the semiconductor and contacts may be required to enhance electron or hole injection. Besides ensuring proper physical connection of the source and drain contacts with the semiconductor, choosing the electrode material is important for the performance of the OTFT device. The combination of contact and semiconductor materials also determines the so-called **contact resistance** between the source and drain. Namely, at the interface between the contacts and the semiconductor material, electronic interaction may cause a shift in the energy levels for charge transport, and herewith the required bias voltages to operate the OTFT.

After completing the OTFT, the device should be properly encapsulated. Many organic materials are very sensitive to moisture and oxygen, and therefore contact with the environment should be avoided.

5.3 OTFT for display manufacturing requirements

Before addressing the technological and manufacturing requirements for OTFT for display, it is important to establish the application requirements, shown in Table 2. Because a questionnaire survey conducted within WP1 of the PRODI project framework together with the industrial advisory board did not yield the required information on the OTFT for display application parameters, part of these requirements were derived from the OE-A roadmap for OTFT for display applications.

Table 2 OTFT for display application parameters.

Application parameter	Value			Unit
	Short term	Medium term	Long term	
Cost	1	0.7	0.5	Silicon
Number of pixels	0.1	1	10	M
Frame refresh rate	1	10	100	Hz
Outline dimension	0.2	0.5	1.0	m ²
Colour range	B/W	Colour	Full colour	
Power consumption	50	20	1	μW/cm ²
Uniformity of drive current	50	10	2	%
Uniformity of output	30	10	2	%
Bend radius	20	10	1	cm
Operational lifetime	10 ²	10 ³	10 ⁴	hours
Shelf lifetime	1	6	12	months
Environmental compliance	Partly	Almost full	Full	

For the short term, product costs should be at least comparable to silicon based TFT solutions to be considered as an alternative to the better performing silicon based solutions. For the short term, we expect application of OTFT only for low-end applications such as labelling whereas as a slow transition to e-paper applications is expected for the medium term. Considering the current status of the material development and available fabrication technology it is only for the long term that

applications such as full colour large area displays can be considered. The parameters in the table translate to technological requirements via a QFD analysis, the results of which are summarized in the following sections. At the time of this study, no information was available on roll to roll manufacturing costs because factory scale manufacturing equipment and accompanying manufacturing statistics simply do not exist. Therefore, the cost requirements were omitted in this study.

5.3.1 Technological requirements and challenges

The technological requirements can be divided into electrical and geometric and material requirements, discussed in the following sections.

5.3.1.1 Electrical requirements

The electrical requirements for OTFT for display technology are shown in Table 3. The application requirements for power consumption translate to the requirements for the drive current I_{on} and the gate voltage. The I_{on}/I_{off} ratio determines the minimum power consumption of the device. The requirements for threshold voltage stability and hysteresis are derivatives of the drive current and output uniformity application parameters. Finally, sub threshold swing and switching frequency are related to the frame refresh rate.

Table 3 Electrical requirements for OTFT for display technology.

Electrical parameter	Value			Unit
	Short term	Medium term	Long term	
I_{on}	10^{-5}	10^{-6}	10^{-7}	A
I_{on}/I_{off}	10^4	10^6	10^8	
Gate voltage	100	50	10	V
Threshold voltage	5	1	0.1	V
Threshold voltage stability	10	5	1	%
Hysteresis	10	5	1	%
Sub threshold swing	N/A	N/A	N/A	V/Dec
Switching frequency	1	10	100	kHz

5.3.1.2 Geometric requirements

The mechanical requirements for OTFT for display technology are shown in Table 4, and are derived from the application parameters for the number of pixels, outline dimension and bend radius.

Table 4 Mechanical requirements for OTFT for display technology.

Feature	Dimension	Value			Unit
		Short term	Medium term	Long term	
Substrate	Vertical	250	100	50	μm
Gate pattern	Vertical	10	1	0.1	μm

	Lateral	100	50	20	μm
	Registration	50	25	10	μm
Dielectric + modifier layer	Vertical	500	100	10	nm
Semiconductor layer	Vertical	1	0.1	0.1	μm
Source/drain pattern	Vertical	10	1	0.1	μm
	Lateral	50	25	10	μm
	Overlay	5	2.5	0.1	μm
Encapsulation layer	Vertical	250	100	50	μm
Overall	Vertical	500	200	100	μm
	Lateral*	0.2	0.5	1	m
	Bend radius	10	2	1	cm

* Total display lateral dimension

5.3.1.3 Material requirements

The material requirements for OTFT for display technology are shown in Table 5. Like the OPV application, the OTFT for display application is very sensitive to oxygen and moisture. The shelf and operation lifetime are therefore related to oxygen transmission rate (OTR) and water vapour transmission rate (WVTR). Furthermore, exposure to UV and temperature cycling affects device performance.

The environmental compliance of the materials is another important aspect. Many conventional semiconductor fabrications technologies involve high emissions of NO_x, particulate matter, and volatile organic compounds. Furthermore, the energy use and the related carbon foot print in the form of CO₂, CH₄ and N₂O emissions are considered as increasingly important parameters. At present no detailed per unit estimates are available, however recent initiatives by the Electronic Industry Citizenship Coalition (EICC), the GHG protocol, and the Carbon Disclosure Project aim at inventorying the emissions of greenhouse gasses and other pollutants for the semiconductor supply chain and manufacturing processes and translate the inventories to per unit footprints. The environmental compliance will be an important application parameter for the short and especially for the long term. It is for this reason that in considering the different manufacturing technologies of OTFT for display, the environmental impact should also be considered.

Table 5 Material requirements for OTFT for display technology.

Material parameter	Value			Unit
	Short term	Medium term	Long term	
Material costs	N/A	N/A	N/A	
Reliability requirements				

OTR	10^{-1}	10^{-2}	10^{-3}	$\text{cm}^3/\text{m}^2/\text{d}$
WVTR	10^{-1}	10^{-3}	10^{-6}	$\text{g}/\text{m}^2/\text{d}$
UV stability	N/A	N/A	N/A	
Temperature stability	N/A	N/A	N/A	
Emission requirements				
NO _x	N/A	N/A	N/A	
CO ₂ /CH ₄ /N ₂ O	N/A	N/A	N/A	
Perfluorinated Compounds (PFCs)	N/A	N/A	N/A	
Volatile Organic Compounds (VOCs)	N/A	N/A	N/A	
Particulate Matter (PM)	N/A	N/A	N/A	

5.3.2 Production process requirements and challenges

This section will discuss possible fabrication techniques for the different features of a BG-TG OTFT, starting with the substrate. For each feature, the frequently used materials and properties, the suitable fabrication methods, and fabrication challenges are discussed. The discussion below is the result of an extensive literature study but does not claim to be exhaustive. Other means to fabricate the different features than summarized here may be available. For patterning process steps, we will focus on ‘standard’ printing technologies, i.e. **flexographic**, **gravure**, **offset**, **screen** and **inkjet** printing. We will evaluate **coating** and **lamination** for process steps involving uniform layers. Additionally, we will look at **evaporation** processes because it is expected that using standard printing technologies to produce certain features (such as the organic layer) in stead, will not lead to devices with comparable performance, not even on the long term. Finally, we will also look at **soft lithography** as an alternative hybrid patterning technique.

5.3.2.1 Substrate pre-treatment and adaptation

Evidently, having a clean and chemically compatible/inactive substrate surface is vital for optimal OTFT device performance. Several methods exist to prepare the surface for processing, as shown in the next section. A couple of intrinsic properties of the substrate surface are essential to control for proper application of the subsequent features, one of which is the surface energy. In the context of manufacturing an OTFT, the surface energy is a parameter that determines whether a surface promotes or inhibits spreading of a given fluid over the surface of the substrate. In the case of water, a surface is called **hydrophilic** when it promotes spreading and **hydrophobic** when it inhibits spreading. Table 6 shows some materials that are used as a substrate for organic electronics manufacturing, together with the surface energies of these materials (source for surface energies: www.surface-tension.de).

Table 6 Surface energy properties of materials used as a substrate for OTFT manufacturing.

Name	Surface free energy at 20 °C [mN/m]
Polyethylene-linear (PE)	35.7
Polyethylene-branched (PE)	35.3
Polypropylene-isotactic (PP)	30.1
Polyisobutylene (PIB)	33.6
Polystyrene (PS)	40.7
Poly-a-methyl styrene (PMS)	39.0
Polyvinyl fluoride (PVF)	36.7
Polyvinylidene fluoride (PVD)	30.3
Polytrifluoroethylene (PTFET)	23.9
Polytetrafluoroethylene (PTFE)	20.0
Polyvinylchloride (PVC)	41.5
Polyvinylidene chloride (PVDC)	45.0
Polychlorotrifluoroethylene (PCTrFE)	30.9
Polyvinylacetate (PVA)	36.5
Polymethylacrylate (PMAA)	41.0
Polyethylacrylate (PEA)	37.0
Polymethylmethacrylate (PMMA)	41.1
Polyethylmethacrylate (PEMA)	35.9
Polybutylmethacrylate (PBMA)	31.2
Polyisobutylmethacrylate (PIBMA)	30.9
Poly(t-butylmethacrylate) (PtBMA)	30.4
Polyhexylmethacrylate (PHMA)	30.0
Polyethyleneoxide (PEO)	42.9
Polytetramethylene oxide (PTME)	31.9
Polyethyleneterephthalate (PET)	44.6
Polyamide-6,6 (PA-66)	46.5
Polyamide-12 (PA-12)	40.7
Polydimethylsiloxane (PDMS)	19.8
Polycarbonate (PC)	34.2
Polyetheretherketone (PEEK)	42.1
Polyethersulfone (PES)	47.0
Polyethylene naphthalate (PEN)	31.0
Polyimide (PI)	36.0
Poly (4-vinylphenol) (PVP)	38.6

The substrate is also the **barrier** between the functional organic features (such as the dielectric and semiconductor) and the environment. Two important parameters are the oxygen transmission rate (OTR) and the water vapour transmission rate WVTR. Foils with a thickness of 50 μm made from the materials shown in Table have typical OTR values between 10^{-1} and 10^{-3} $\text{cm}^3/\text{m}^2/\text{day}/\text{atm}$ and typical WVTR values between 10^{-1} and 10^{-3} $\text{g}/\text{m}^2/\text{day}$. For normal packaging purposes, these values are sufficient. In food packaging, the lower bound of these values is already required. For organic electronics however, OTR values $<10^{-3}$ $\text{cm}^3/\text{m}^2/\text{day}/\text{atm}$ and WVTR values $<10^{-6}$ $\text{g}/\text{m}^2/\text{day}$ are required for product lifetimes of order 10^4 hours.

This means that the application of additional layers, such as alternating polyacrylate/ Al_2O_3 stacks, to suppress the oxygen and water permeability is required to ensure prolonged operation of the device. Different **coating** techniques (self metered, doctored, pre metered) such as reverse roll, Mayer bar, or slot die coating can be used to add these **barrier** layers on the substrate surface. Alternatively, the use of inorganic

gate electrodes and dielectric (such as SiO₂) with lower gas and vapour permeability can be considered.

Besides the surface energy, the surface roughness of the substrate is an important parameter determining the OTFT performance. Some materials, e.g. polyimide (PI), are also suitable as gate dielectric. In that case, the gate electrode can be patterned on the backside of the substrate. Surface roughness affects the final grain size of the deposited semiconductor and also the formation of charge traps at the interface between the dielectric and the semiconductor. Hence, surface roughness should be minimized. Typical values of the surface roughness of the materials in Table are between 0.1 and 10 nm. Ideally, surface roughness after treatment or modification should be of order 0.1 nm, or less.

Overall, the order of magnitude of the values of the relevant parameters for the short, medium and long term are shown in Table 7, the short term being characterized by the values that are considered feasible with the state of the art technology.

Table 7 Basic property requirements for substrate before processing.

	Short term	Medium term	Long term
Thickness [μm]	250	100	50
Roughness [nm]	10	1	0.1
Surface energy [mN/m]	50	75	100
Max. Temperature [$^{\circ}\text{C}$]	200	200	200
WVTR [$\text{g}/\text{m}^2/\text{day}$]	10^{-1}	10^{-3}	10^{-6}
OTR [$\text{cm}^3/\text{m}^2/\text{day}/\text{atm}$]	10^{-1}	10^{-2}	10^{-3}

Depending on the substrate, the following methods are generally used to prepare the substrate for processing:

- Adhesive cleaning
- Chemical Mechanical Polishing (CMP)
- Ultrasonic cleaning in solutions such as
 - Acetone,
 - Trichloroethylene
 - HNO₃
 - Methanol
 - Deionized water
- UV/ozone photochemical cleaning
- Ion beam cleaning
- Corona plasma treatment in oxidizing atmosphere (e.g. in O₂ or N₂)
- De-ionization

Finally, the substrate is dried in an dry N₂ environment. All cleaning methods should ensure removal of contaminants as well as surface charges as these will attract new contamination during processing. Ideally, processing should start immediately after cleaning.

Table 8 Challenges for substrate treatment before processing.

Challenges	Solutions
WVTR	Use appropriate substrate material Use appropriate substrate thickness Add barrier layers
OTR	Use appropriate substrate material Use appropriate substrate thickness Add barrier layers
Surface roughness	Use appropriate substrate material Add coating layers to reduce roughness
Surface energy	Corona plasma treatment
Surface cleanliness	Use appropriate cleaning techniques

5.3.2.2 Gate patterning and curing

Layer materials and properties

In the literature, different materials are reported as gate contact material. Besides heavily doped Si, Al, Cr, Mo, Cu, indium-tin oxide (ITO) and Poly (3, 4-ethylenedioxythiophene)-Polystyrene Sulfonate (PEDOT:PSS), materials like polyaniline (PANI) or combinations of Poly (3, 4-ethylenedioxythiophene)-Polystyrene Sulfonate (PEDOT:PSS) with dimethyl sulfoxide (DMSO) and PEDOT:PSS with Polydimethylsiloxane (PDMS) stamps were also found. Although gate and gate dielectric are frequently used almost synonymously, we will consider the gate and dielectric as two different features. The dielectric layer will be considered in the next section.

In order to minimize the overall thickness of the OTFT device, the thickness of the gate contact should be minimized. However, current fabrication techniques such as evaporation or laser transfer already allow for layer thicknesses of order 0.1 μm . On the long term, the gate lateral dimensions should approach values below discernible visible resolution within a register of 1 μm to enable application of OTFT's for full colour displays.

The electrical resistance of the gate pattern should be minimized, preferably to values comparable to bulk material conductivity values. Low values are not mandatory because the resistance of the gate is not expected to be an important limiting factor for OTFT device performance. The requirement for the low resistance value of the gate contact high solid percentage lead to a preferentially high solid content of the printing fluid which leads to relatively large equivalent viscosities.

The choice of the gate contact material is not arbitrary (Pernstich, 2004) The energy required for charge injection is dependent on the Fermi level (E_F) of the gate material, the vacuum energy level (E_V), the highest occupied molecular orbital (HOMO), and the lowest unoccupied molecular orbital (LUMO) of the semiconductor, see Figure :

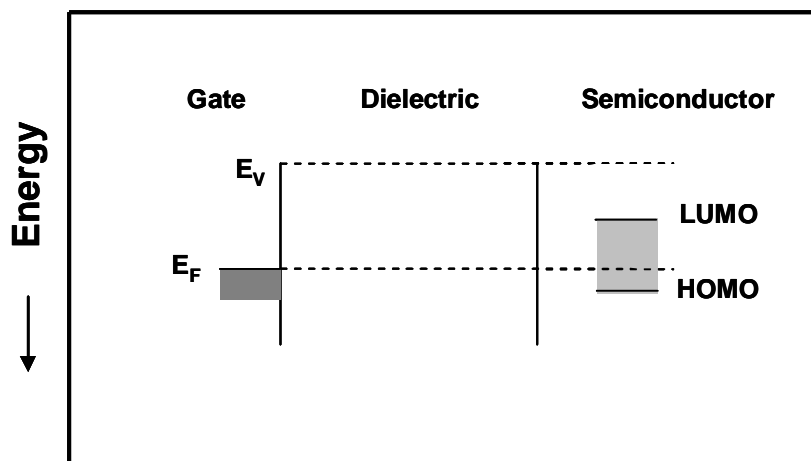


Figure 5 Energy levels of gate contact-dielectric-semiconductor interface

The distance between the Fermi level and the HOMO or LUMO levels of the semiconductor determines the required energy barrier to form a conducting electron or hole channel at the interface between the dielectric and the semiconductor. If the Fermi level is closer to the HOMO energy level, a hole channel is more easily formed whereas when the Fermi level is closer to the LUMO energy level, an electron channel is more easily formed. The gap between the Fermi level and the HOMO or LUMO should be minimized to minimize the **threshold voltage**. Therefore it is important to **match** the contact material to the materials that are used for the dielectric and the semiconductor layer.

Finally, the surface energy should be maximized to enable smooth application of the dielectric layer. Surface roughness should be minimized to ensure proper electrical connection between the gate dielectric and the gate contact and to enable precise overlay of the source and drain contacts.

In Table 9 the requirements for the gate pattern are summarized.

Table 9 Property requirements for the gate pattern.

	Short term	Medium term	Long term
Thickness [μm]	10	1	0.1
Lateral dimensions [μm]	100	50	20
Registration [μm]	50	25	10
Material choice	Matched	Matched	Matched
Resistance [$\text{n}\Omega\text{m}$]	28 (Al)	Minimized	Minimized
Viscosity [mPas]	10	50	100
Roughness [nm]	10	1	0.1
Surface energy [mN/m]	50	75	100

Suitable deposition and drying methods

For conventional printing techniques, a layer thickness in the range of $0.1\mu\text{m}$ is feasible for relatively low viscosities (i.e. large water content). However, unifying the thickness requirement with the requirements for lateral feature size, registration, and low electrical resistivity (and herewith the accompanying large solid content of the printing fluid) is technically challenging. At present, none of the regular printing methods considered here are able to meet the long term requirements. Some of the printing methods are marginally able to meet the medium term requirements. For the short and medium term, **gravure** and **offset** printing are expected to be most suitable for the

deposition of the gate contacts (see Table 10). In principle, the two alternative deposition methods considered here - **evaporation** and **soft lithography** - are very suitable for depositing the gate contact, however the roll to roll applicability of these deposition methods is still under development whereas the regular printing methods are inherently roll to roll compatible.

If regular printing techniques are used, the solvent is removed by evaporation in a dry atmosphere and/or at elevated uniform temperature. Uniform removal of the solvent requires uniform temperature and vapour pressure above the layer surface.

Table 10 Advantages and disadvantages of the different deposition methods for the gate pattern.

Printing method	Advantages	Disadvantages
Gravure	Good viscosity range Good layer thickness Reasonable feature size Good registration Good speed	
Screen	Good viscosity range	Poor layer thickness Poor feature size Poor registration Poor speed
Inkjet	Good viscosity range Good layer thickness Good feature size Good registration	Very poor speed
Offset	Good viscosity range Reasonable layer thickness Good feature size Good registration Good speed	
Flexography	Good viscosity range Good layer thickness Reasonable feature size Good speed	Poor registration
Lamination	Not applicable	Not applicable
Coating	Not applicable	Not applicable
Evaporation	Excellent layer thickness Excellent feature size Excellent registration	Poor speed Requires vacuum environment R2R incompatible at present
Soft lithography	Excellent layer thickness Excellent feature size Excellent registration	Poor speed Requires vacuum environment R2R incompatible at present

Process challenges

Table 11 summarizes the process challenges and solutions for gate patterning. It is expected that for the short and medium term requirements, the challenges can be tackled by optimizing existing printing methods (i.e. by reducing substrate processing speed and surface area, by matching the materials, etc.), but on the long term, technological innovations are necessary to close the gap between the state of the art capabilities and the requirements.

Table 11 Process challenges for the gate pattern.

Challenges	Solutions
Low resistivity	High solid content of printing fluid Increase layer thickness
Feature size	Use proper printing technique, gravure or offset, or alternatively, evaporation or soft lithography
Registration	Use proper printing technique Use adequate registration measurement and control
Surface roughness	Use proper printing technique Ensure proper curing
Surface energy	Use proper materials Use proper post treatment (e.g. corona plasma treatment)

5.3.2.3 Dielectric/modifier layer deposition and curing

Layer materials and properties

The dielectric layer is typically deposited using techniques like spin coating, evaporation, sputtering, ion beam deposition. Amongst the fabrication technologies considered here, coating techniques are very suitable for the deposition of this layer. Materials that were found in the literature are Poly(methyl methacrylate) (PMMA), Polyvinyl alcohol (PVA), SiO₂ SiN_x, Al₂O₃ with polystyrene (PS), Mylar®, poly-4-vinylphenol and poly(melamine-co-formaldehyde) methylated in n-butanol, polyester, methyl-siloxane-based spin-on glass, poly (4-vinylphenol) (PVP), polyimide (PI), Polyvinylidene Fluoride (PVDF), Acryl, methacryl-grafted hybridizers (MD), Ta₂O₅, and HfO₂.

The thickness is an important parameter that should be minimized to increase the capacitance of the dielectric, see Section 5.2.3. However, direct and Fowler-Nordheim tunnelling processes, responsible for gate current leakage, and the dielectric breakdown limit constrain the reduction of the dielectric layer thickness to the nanometre scale. Depending on the material properties of the dielectric, lower limits of the order of 10 nm are expected for the long term, whereas currently, state of the art literature frequently reports dielectric layer thickness in the order of 500 nm.

Preferably, the dielectric constant is maximized but the extend is limited because most polymers have dielectric constants in the range between 2 and 5. For the long term applications, this parameter is usable to maximize device performance. It is noted that some inorganic materials with high dielectric constants, such as Ta₂O₅, cause more charge self trapping due to polarization effects at the interface between the dielectric and the semiconductor. Furthermore, full inorganic dielectric layers limit flexible substrate processing and the materials are often incompatible with the other – organic – materials used to fabricate the other device features. Polymer dielectric modifier layers are frequently used to combine the high dielectric constant associated with the inorganic dielectric with the processing advantages associated with the organic dielectric modifier layer. The following material combinations for the dielectric and modifier layer were found in the literature:

- Silicon-nitride deposited in a layer of 35 nm modified with a PMMA modifier layer of 10 nm.
- AlO_x deposited in a layer of 100 nm with a PVP modifier layer of 45 nm.
- PVA deposited in a layer of 630 nm with a PMMA modifier layer of 23 nm.
- Tantalum pentoxide (Ta₂O₅) with a PFN modifier layer of 40 nm.
- ITO with PVP.
- PVP with PI.
- PVP with PVA.
- polystyrene (PS) with HfO₂ (Hafnium dioxide).
- SiO₂ in layers between 10-100 nm with a PVA modifier layer of 95 nm.
- Hexamethyldisilazane (HDMS) on a SiO₂ layer of 60 nm.
- AlO_x with a Self Assembled Monolayer (SAM) of 2-propanol.

Several advantages are reported on using organic modifier layers. For example, pentacene layers grown on organic layers of PMMA with a surface slightly more hydrophobic than have more molecular organization and larger grain sizes, resulting in higher carrier mobility (Deman et al., 2008). Many research groups are investigating the application of self assembled monolayers (SAM's) to prepare the dielectric surface for deposition of the semiconductor material. However, some controversy exists about whether surface energy should be minimized or maximized to create efficient organic semiconducting layers. The only meaningful requirement we can give for the surface energy of the dielectric/modifier layer is that it should be optimized for the organic material that is used for the semiconductor layer.

The impact of the tunnelling processes described in the text above, is also dependent on the dielectric surface roughness, which should therefore be minimized. The viscosity of the dielectric/modifier material should also be maximized because the presence of the solvents may affect the layer fabrication process. In spin coating, for example, excessive solvent evaporation during processing lead to layer imperfections. Because the current will flow mainly at the interface between the semiconductor and modifier/dielectric layer, any discontinuity at this interface will decrease OTFT device performance due to charge trapping. The final reason to reduce surface roughness of the dielectric/modifier layer is the subsequent deposition of the semiconductor layer. Surface roughness should be significantly smaller than the layer thickness requirements because the long term requirements for OTFT device geometry demand for great vertical uniformity. In Table 2, the requirements are summarized.

Table 12 Property requirements for the dielectric/modifier layer.

	Short term	Medium term	Long term
Thickness [nm]	500	100	10
Dielectric strength [MV/m]	10	50	100
Dielectric constant [-]	3	10	20
Viscosity [mPas]	10	50	100
Roughness [nm]	10	1	0.1
Surface energy [mN/m]	Optimized	optimize	optimize

Suitable deposition and drying methods

As was already mentioned the previous section, coating techniques are expected to be most suitable for the deposition of the dielectric/modifier layer. However, the medium and long term requirements for layer thickness will pose problems for state of the art equipment. The medium and long term requirements demand for highly controlled solvent evaporation from the coated layers that typically have a wet thickness in the range 1-20 μm , which is infeasible in roll to roll processing equipment at present.

Assuming that the gate surface roughness is small, coating techniques such as **wire wound**, **reverse roll**, **air knife**, and **blade coating** can be considered (see Table 3). The mechanical load involved with the doctored coating techniques should be minimized to avoid damage to the features already present on the substrate. On the other hand, if the gate vertical geometry variations are sufficiently small, good layer properties may also be achieved with uniformly patterned **gravure** or **flexographic** printing. Finally, evaporation techniques are in principle suitable for deposition of the dielectric/modifier layer but at present, roll to roll compatibility is limited.

Table 13 Advantages and disadvantages of the different deposition methods for the dielectric/modifier layer.

Printing method	Advantages	Disadvantages
Gravure	Good viscosity range Excellent wet layer thickness Good speed	Potential ink transfer problems, i.e. missing dots
Screen	Good viscosity range	Poor layer thickness Poor speed
Inkjet	Good viscosity range Good layer thickness	Very poor speed
Offset	Good viscosity range Reasonable layer thickness Good speed	
Flexography	Good viscosity range Good layer thickness Good speed	Poor solvent resistance of the plates
Lamination	Good speed	Poor layer thickness Possible connectivity problem
Coating	Good viscosity range Good layer thickness Good speed	
Evaporation	Excellent layer thickness	Poor speed R2R incompatible at present
Soft lithography	Excellent layer thickness	More suitable for patterning Poor speed R2R incompatible at present

Production process challenges

Table 4 summarizes the process challenges and solutions for fabrication of the dielectric/modifier. It is expected that for the short and term requirements, the challenges can be tackled by optimizing existing printing methods (i.e. by reducing substrate processing speed and surface area, by matching the materials, etc.), but on the medium and long term, technological innovations are necessary to close the gap between the state of the art capabilities and the requirements.

Table 14 Process challenges for the dielectric/modifier layer.

Challenges	Solutions
Uniform layer	Minimize initial wet layer thickness. Optimize drying procedure. Use compatible materials.

5.3.2.4 Semiconductor layer deposition and curing

Layer materials and properties

The semiconductor layer is the central functional part of the OTFT device. It must be a good insulator in the off-state whereas it must be a good conductor in the on-state. The conductivity (either p- or n-type) in the off-state is an important parameter for the off-current (I_{off}) of the OTFT and is essentially inherent to the choice of the semiconductor material. The channel width, the channel length and the bias voltage between the source and the drain then determine the off-current. Uniformity of the organic layer is very important. Many studies aim for high levels of molecular organisation/crystallinity by using highly sophisticated surface modification, deposition and post processing techniques because it is generally believed that this will maximize the carrier mobility. Recent studies show however, that the grain size of crystalline structures, is not the sole parameter determining carrier mobility but that sub-grain microstructure, i.e. molecular organization may be the dominant limiting factor (Cheng et al., 2009). Further scientific research on this topic is required to obtain the fundamental insights in organic TFT device operation. Another reason to strive for high levels of molecular organisation is that the electric properties in general are homogenized. It is expected that other loss processes, like **punch trough**, an increase in drain current due to uncontrollable parasitic current paths between the drain and source, are reduced.

In literature, pentacene is very often reported as semiconductor material for OTFT manufacturing. This is mainly because this material has produced the best performing OTFT with carrier mobilities of over $1 \text{ cm}^2/\text{V}\cdot\text{s}$. Other materials are tetracene, polythiophenevinylene (PTV), oligothiophenes, Regioregular poly (thiophene) XPS, organic-inorganic hybride materials., Dihexylsexithiophene, Poly(3-hexylthiophene) (P3HT), Polyfluorene-based polymers, Regioregular poly(3-hexylthiophene) (PHT), and Perylene tetracarboxylic diimide (PTCDDI). Carrier mobilities of these materials are generally in the range between 0.01 and $1 \text{ cm}^2/\text{V}\cdot\text{s}$, with **Ion/Ioff** ratios between 10^4 and 10^6 . State of the art mobilities in principle meet the short term requirements, but the fabrication methods used to achieve these performances, e.g. by attaching the flexible substrate to a rigid substrate to enable accurate high vacuum processing, are not compatible with roll to roll processing. Therefore, current applicability of OTFT, even for basic display technology, is very limited. For the medium and long term applications, carrier mobilities should be improved drastically to the range of $10\text{-}100 \text{ cm}^2/\text{V}\cdot\text{s}$., requiring scientific breakthroughs.

Table 15 Property requirements for the semiconductor layer.

	Short term	Medium term	Long term
Thickness [μm]	1	0.1	0.01
Carrier mobility [$\text{cm}^2/\text{V}\cdot\text{s}$]	1	10	100
Viscosity [mPas]	10	50	100
Roughness [nm]	10	1	0.1
Surface energy [mN/m]	50	75	100

Suitable deposition and drying methods

Like the deposition of the dielectric/modifier layer coating techniques are expected to be most suitable for the deposition of the semiconductor layer. Similar limitations apply and therefore a similar set of printing techniques would be most suitable for the short term requirements. The medium and long term requirements are not achievable without technological breakthroughs in fabrication and material technology.

Table 16 Advantages and disadvantages of the different deposition methods for the semiconductor layer.

Printing method	Advantages	Disadvantages
Gravure	Good viscosity range Excellent wet layer thickness Good speed	Potential ink transfer problems, i.e. missing dots
Screen	Good viscosity range	Poor layer thickness Poor speed
Inkjet	Good viscosity range Good layer thickness	Very poor speed
Offset	Good viscosity range Reasonable layer thickness Good speed	
Flexography	Good viscosity range Good layer thickness Good speed	Poor solvent resistance of the plates
Lamination	Good speed	Poor layer thickness Possible connectivity problem
Coating	Good viscosity range Good layer thickness Good speed	
Evaporation	Excellent layer thickness	Poor speed R2R incompatible at present
Soft lithography	Excellent layer thickness	More suitable for patterning Poor speed R2R incompatible at present

Production process challenges

Table 7 summarizes the process challenges and solutions for fabrication of the semiconductor layer. It is expected that for the short and term requirements, the challenges can be tackled by optimizing existing printing methods (i.e. by reducing substrate processing speed and surface area, by matching the materials, etc.), but on the medium and long term, technological innovations are necessary to close the gap between the state of the art capabilities and the requirements.

Table 17 Process challenges for the semiconductor layer.

Challenges	Solutions
Uniform layer	Minimize initial wet layer thickness Optimize drying procedure Use compatible materials

5.3.2.5 Source and drain patterning and curing

Layer materials and properties

After the semiconductor layer, the source and drain are patterned. Materials like Poly (3, 4-ethylenedioxythiophene)-Polystyrene Sulfonate (PEDOT:PSS), PEDOT:PSS mixed with dimethyl sulfoxide (DMSO), PEDOT:PSS applied with Polydimethylsiloxane (PDMS) stamps, polyaniline (PANI), Au, Al, Ni, Ag, C, indium-tin oxide (ITO), and Al doped ZnO (AZO) were frequently found in literature. Furthermore, Ti/Cr are often used as adhesives to improve the electric connection between the contacts and the semiconductor. In the case that an ambipolar semiconductor is used, an intermediate patterning of a n- or p-doped layer is required to reduce the energy threshold for either electron or hole injection from the source contact to the semiconductor.

It is important to note that the choice of the source/drain contact material is not arbitrary. To explain why, some basic OTFT theory is in place (Klauk, 2006) The energy required for charge injection is dependent on the Fermi level (E_F) of the contact material, the highest occupied molecular orbital (HOMO), and the lowest unoccupied molecular orbital (LUMO), see Figure 7:

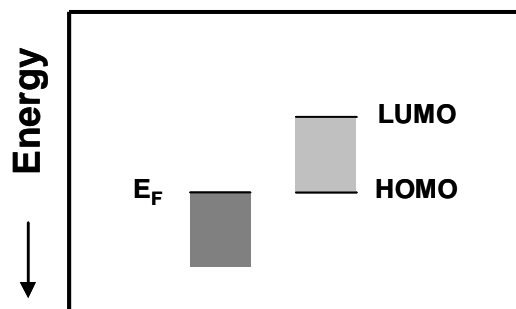


Figure 7 Energy levels of contact-semiconductor interface.

Depending on the distance between the Fermi level and the HOMO or LUMO levels of the semiconductor, the required injection energy barrier of either electrons or holes may be large. If the Fermi level is closer to the HOMO energy level, holes are more easily injected than electrons whereas when the Fermi level is closer to the LUMO energy level, electrons are more easily injected than holes. In the first case, the semiconductor is said to be of p-type, in the latter case the semiconductor is said to be of n-type. When the distance is equal, the semiconductor is ambipolar. At the interface between the organic semiconductor and the contacts, the electronic interactions may cause shifts in the energy levels of the semiconductor, that may lead to increased energy barriers for charge injection, resulting in larger **contact resistance**. Therefore it is important to **match** the contact material to the materials that are used for the dielectric and the semiconductor layer.

A crucial parameter for OTFT device performance is the overlay. The source/drain patterns should be precisely oriented with respect to the gate contact and with one and another. As was discussed in Section 5.2.3, having a short channel length is vital for good performance. Also, the effective surface area of overlap between the source and drain contacts and the gate is an important parameter for OTFT device performance.

Viscosity is again ideally maximized to reduce solvent evaporation effects on the quality of the morphology of the source/drain contacts. Roughness is again minimized. The surface energy is maximized for the subsequent coating/lamination step for encapsulation.

Table 28 Property requirements for the source/drain patterns.

	Short term	Medium term	Long term
Thickness [μm]	10	1	0.1
Lateral dimensions [μm]	50	25	10
Material choice	Matched	Matched	Matched
Overlay [μm]	5	2.5	0.1
Viscosity [mPas]	10	50	100
Roughness [nm]	10	1	0.1
Surface energy [mN/m]	50	75	100

Suitable deposition and drying methods

Like the deposition of the gate pattern, **gravure** and **offset** printing techniques are expected to be most suitable for the deposition of the source/drain patterns that meet the short term requirements. The medium and long term requirements are not achievable without technological breakthroughs in fabrication and material technology. Current Optical lithography tools used in semiconductor processing can meet the specifications, but need to be adapted for roll to roll manufacturing. Especially the overlay requirement is problematic from the actual printing process point of view (in terms of registration and resolution) and even limits production scale fabrication of OTFT's meeting the short term requirements. From the manufacturing point of view, the flexible substrates will also require very precise handling and monitoring. This is not possible using state of the art technology. **Evaporation** and **soft lithography** are in principle very suitable techniques, but are yet to be adapted for roll to roll manufacturing.

Table 19 Advantages and disadvantages of the different deposition methods for the source/drain patterns.

Printing method	Advantages	Disadvantages
Gravure	Good viscosity range Good layer thickness Reasonable feature size Good registration Good speed	
Screen	Good viscosity range	Poor layer thickness Poor feature size Poor registration Poor speed
Inkjet	Good viscosity range Good layer thickness Good feature size Good registration	Very poor speed
Offset	Good viscosity range Reasonable layer thickness Good feature size Good registration Good speed	
Flexography	Good viscosity range Good layer thickness Reasonable feature size Good speed	Poor registration
Lamination	Not applicable	Not applicable
Coating	Not applicable	Not applicable

Evaporation	Excellent layer thickness Excellent feature size Excellent registration	Poor speed Requires vacuum environment R2R incompatible at present
Soft lithography	Excellent layer thickness Excellent feature size Excellent registration	Poor speed Requires vacuum environment R2R incompatible at present

Production process challenges

In Table 20, the process challenges and solutions associated with source/drain patterning are shown.

Table 20 Process challenges for the source/drain patterns.

Challenges	Solutions
Feature size	Use proper printing technique, gravure or offset, or alternatively, evaporation or soft lithography
Overlay	Use proper printing technique Use adequate registration measurement and control
Surface roughness	Use proper printing technique Ensure proper curing
Surface energy	Use proper materials Use proper post treatment (e.g. corona plasma treatment)

5.3.2.6 Encapsulation patterning and curing

Layer materials and properties

The final feature is the encapsulation of the OTFT because the performance is easily degraded due to oxygen and water. Therefore, WVTR and OTR requirements similar to the requirements for the substrate permeability apply. In principle, the OTFT will be used in combination with the display technology and encapsulation is provided by the features deposited on top of the OTFT device. In literature, the individual performance is often monitored and materials like Polyvinyl acetate (PVA), Silicon nitride (SiN), and parylene were found used for encapsulation. The layer thickness should be limited to meet the overall thickness requirements for the OTFT device. In the case of subsequent application of the display functionality, the encapsulation layer is used as planarization layer for which roughness should be minimized and surface energy should be maximized.

Table 21 Property requirements for the encapsulation layer.

	Short term	Medium term	Long term
WVTR [g/m ² /day]	10 ⁻¹	10 ⁻³	10 ⁻⁶
OTR [cm ³ /m ² /day/atm]	10 ⁻¹	10 ⁻²	10 ⁻³
Thickness [μm]	250	100	50
Roughness [nm]	10	1	0.1
Surface energy [mN/m]	50	75	100

Suitable deposition and drying methods

When the encapsulation layer is the final sealant, the requirements for layer thickness, surface roughness and surface energy are less strict. In that case **coating** and **lamination** are most preferable, but other printing techniques can also be used. The use

of inkjet printing is not recommended because it is not suitable for large area continuous processing of thick layers. If the encapsulation layer is used as a planarization layer, fewer options remain because of the requirements for layer thickness, surface roughness and surface energy. Similar techniques as for the dielectric layer would be most suitable with the difference that proper isolation from the environment is more important than connectivity with the underlying features. This is because in this case, only the mechanical aspects of the connectivity are important.

Table 22 Advantages and disadvantages of the different deposition methods for the encapsulation layer.

Printing method	Advantages	Disadvantages
Gravure	Good viscosity range Excellent wet layer thickness Good speed	Potential ink transfer problems, i.e. missing dots
Screen	Good viscosity range	Poor layer thickness Poor speed
Inkjet	Good viscosity range Good layer thickness	Very poor speed
Offset	Good viscosity range Reasonable layer thickness Good speed	
Flexography	Good viscosity range Good layer thickness Good speed	Poor solvent resistance of the plates
Lamination	Good speed	Poor layer thickness Possible connectivity problem
Coating	Good viscosity range Good layer thickness Good speed	
Evaporation	Excellent layer thickness	Poor speed R2R incompatible at present
Soft lithography	Excellent layer thickness	More suitable for patterning Poor speed R2R incompatible at present

Production process challenges

The production challenges are shown in Table 23.

Table 23 Process challenges for the encapsulation layer.

Challenges	Solutions
WVTR	Use appropriate substrate material Use appropriate substrate thickness Add barrier layers
OTR	Use appropriate substrate material Use appropriate substrate thickness Add barrier layers
Surface roughness	Use appropriate substrate material Add coating layers to reduce roughness
Surface energy	Corona plasma treatment
Surface cleanliness	Use appropriate cleaning techniques

5.4 Conclusions

All production requirements require improvements to meet the short, medium and long term requirements:

- The layer thickness range of 10-100 nm is still difficult to manage accurately, because all conventional techniques produce wet layers in the μm range. Uniform controlled evaporation is vital for final layer/pattern quality.
- Registration and overlay accuracy capabilities are currently limited so that even the short term requirements are difficult to meet.
- The size of the different device features, especially the channel length, are critical parameters. Because of limited resolution, conventional printing techniques require big improvements for the medium and long term requirements.
- If evaporation and lithography techniques can be made compatible with roll to roll processing, these technologies are potentially.

Technological breakthroughs are required for the medium and long term requirements:

- The operation of the device related to feature structure is still not understood. It is important that the critical device parameters are determined before a unambiguous set of requirements can be derived.
- The semiconductor materials require much higher charge carrier mobility. Hence, new material development is vital for the organic technology for display applications.
- Online monitoring of large area electronics manufacturing is very challenging because of the range of geometric scales and the flexible substrate dynamics. Traditional accurate monitoring systems are at present most suitable for small area inspection and require technological innovations to meet the new requirements.

5.5 Selected publications

Cheng, H.-L., Liang, X.-W., Chou, W.-Y., Mai, Y.-S., Yang, C.-Y., Chang, L.-R., Tang, F.-C. (2009) Raman spectroscopy applied to reveal polycrystalline grain structures and carrier transport properties of organic semiconductor films: Application to pentacene-based organic transistors, *Organic Electronics*, **10**, 289-298.

Deman, A.-L., Erouel, M., Lallemand, D., Phaner-Goutorbe, M., Lang, P., Tardy, J. (2008) Growth related properties of pentacene thin film transistors with different gate dielectrics, *J. Non-Crystalline Solids*, **354**, 1598-607.

Gupta, D., Katiyar, M., Gupta, D. (2009) An analysis of the difference in behaviour of top and bottom contact organic thin film transistors using device simulation, *Organic Electronics*, **10**, 775-784.

Hwang, D.K., Oh, M.S., Hwang, J.M., Kim, J.H., Im, S. (2008) Hysteresis mechanisms of pentacene thin-film transistors with polymer/oxide bilayer gate dielectrics, *Appl. Phys. Lett.*, **92**, 013304.

Klauk, H. [Editor] *Organic Electronics, Materials, Manufacturing and Applications*, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, ISBN: 3-527-31264-1, 2006.

Pernstich, K.P., Haas, S., Oberhoff, D., Goldmann, C., Gundlach, D.J., Batlogg, B., Rashid, A.N., Schitter, G. (2004) Threshold voltage shift in organic field effect transistors by dipole monolayers on the gate insulator, *J. Appl. Phys.*, **96**, 6431, DOI:10.1063/1.1810205.

6 Related material

6.1 Information acquisition

This chapter discusses information acquisition methods used by the consortium in implementing the WP1 tasks, of which result are contained in this deliverable report.

6.1.1 Survey

The consortium's initial approach to information acquisition was an implementation of a survey targeted at companies and R&D organisation in the field of printed and organic electronics. The target was to obtain feedback technological capabilities and requirements for printed and organic electronics manufacturing equipment. The task of developing the survey was coordinated by Acreo of Sweden and implemented actively by the consortium.

Organisation												
Name												
email address												

Please indicate the relevance for the selected processes/techniques for each application in table. Use 0,1, and 2 according to the following:

Not relevant	0
Possible	1
Preferred	2

Applications	Comments	Gravure	Screen	Ink Jet	Offset	Flexo	Lamination	Coating	Laser ablation	Embossing/impacting	Dpp
1 Electronic circuitry											
2 Integrated circuits											
3 Batteries											
4 Solar cells											
5 LEDs											
6 Large area sensors											
7 Displays											
WEIGHT		0	0	0	0	0	0	0	0	0	0

Please fill in the table with details relevant for the processes/techniques available from your organization or with values required by you as component manufacturer. Address the most applicable processes you don't necessary have to fill in them all. Address also large dimensions, applications to cover walls etc.

The values to fill in should be for the printing processes. They are later going to be compared with values for photolithographic processes as a reference.

Parameters	Comments	Gravure	Screen	Ink Jet	Offset	Flexo	Lamination	Coating	Laser ablation	Embossing/impacting	Dpp	R2R Photolithography as reference
1 Registration accuracy over a complete manufacturing line to define the whole system performance	Specify the in-line registration capability in the web direction in μm .										50,0	5
	Specify the in-line registration capability cross the web direction in μm .										50,0	5
2 Thickness range	Specify the wet ink thickness range in μm .											n.a.
3 Feature size range	Specify the minimum and maximum feature size.											min. 5 μm
4 Web width	Specify the web width in mm.										n.a.	n.a.
5 Web speed m/min	Specify both minimum and maximum web speed in m/min.										180 m/min	1 m/min
6 Unit costs	Specify the cost for the equipment unit.										3 ME	1.1 ME
7 Printing surface characteristics (link to materials roadmap)	Specify the surface characteristics needed and if any pre-treatment is necessary/possible. (surface roughness, wettability, Surface energy etc)										Most flexible materials	n.a.
8 Ink characteristics (organic, inorganic; link to materials roadmap)	Specify the possible ink type that are possible to use (organic, inorganic, water based, solvent based etc.)										n.a.	n.a.

Figure 1. Facsimile of the survey.

The questionnaire form contained two different parts. In the first part the respondents were asked to weigh different printing technologies and their relevance for different applications. In the second part the respondents were asked to provide more specific quantified process data for the evaluated printing technologies. Photolithography

process parameters were given as reference values. The group of target companies for the survey comprised the following companies

Table 1. A list of targeted companies.

Name	Related products	Production technology
Agfa Gevaert N.V	Materials	Inkjet printing
ASEM Mühlbauer GmbH	RFID	Offset printing
ASML Netherlands B.V.		Lithography
AVT		Inspection
Coatema		Various
Coherent Inc.		Laser
Fujifilm Dimatix		Inkjet
Fujifilm Sericol	Materials	Inkjet
GSI Technologies	EL, RFID, PV	Printing
Honeywell Specialty Materials	Materials	
MAN Roland		Materials
M-SOLV Ltd		Laser ablation
Nilpeter AS		Manufacturer of roll to roll print equipment
ORFID	VOFET, RFID	Printing
Plastic Electronic GmbH	Sensors	Roll-to-roll
PolyIC GmbH & Co. KG	RFID, smart objects	Printing, hot stamping
Printed Systems GmbH	NF-IP	Printing
Thin Film Electronics	Memory, electronics	Printing
Veeco Instruments GmbH		Various
Xaar	Various	Inkjet
3D AG		Holographic solutions, micro- and nanotechnology

6.1.2 Survey results

The table below is a summary of the answers received in the survey. As indicated by the below chart Gravure, Screen and Flexo printing were considered the most versatile printing technologies. Offset is an interesting technology but not considered as preferred for any of the applications listed. Technologies are also more or less preferred dependent on the application. Ink jet is on fourth place as relevant technology, this is probably a reflection of the fact that ink jet is a relative new technology and not as mature as the three first. Though the potential for ink jet is high being a more digital method and with the possibility for high resolution and narrow line width. Ink development and other technology advances to enable small drop sizes are needed for this printing method to overtake the number one position.

Applications	Gravure		Screen		Ink Jet		Offset		Flexo		Lamination		Coating		Laser ablation		Embossing / imprinting		DPP		Legend
	1's	2's	1's	2's	1's	2's	1's	2's	1's	2's	1's	2's	1's	2's	1's	2's	1's	2's	1's	2's	
Electronic circuitry	2	3	2	2	4	1	4	0	3	3	1	2	1	2	1	2	3	1	1	0	Highly relevant
Integrated circuits	1	3	2	0	4	1	4	0	3	0	2	0	2	0	1	2	1	1	1	0	Relevant
Batteries	1	1	2	3	4	0	2	0	2	0	2	3	0	1	0	0	0	1	0	Relevant	
Solar cells	4	2	5	0	2	1	5	0	6	0	2	1	2	1	2	1	1	1	0	Relevant	
LEDs	3	1	4	0	3	0	5	0	4	1	0	2	3	1	1	1	1	0	1	0	Relevant
Large area sensors	4	1	4	2	3	2	6	0	4	2	1	1	3	0	2	1	3	0	1	0	Relevant
Displays	1	1	3	2	1	3	4	0	4	1	1	2	2	1	1	1	2	1	1	0	Interesting
Total	16	12	22	9	21	8	30	0	26	7	7	10	16	5	9	8	11	4	7	0	
WEIGHT	40		40		37		30		40		27		26		25		19		7		

Figure 2. Summary of the survey.

From the diagram below one can read that Gravure and Flexo are considered the best technologies for producing electronic circuitry. It is also deemed possible to use Inkjet and Offset technologies. The survey indicated also that integrated circuits are best produced using Gravure but many of the answers also point towards Inkjet and Offset being interesting technologies to use. For battery manufacturing the foremost preferred technology is screen printing. There is also a general understanding that Ink jet is possible to use although it is not the preferred technology.

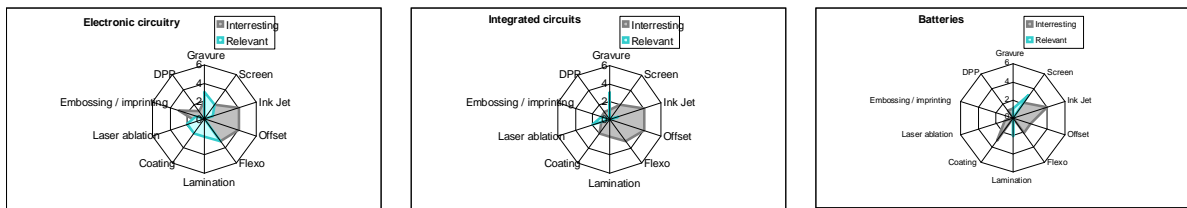


Figure 3. Preferred printing methods for producing electronic and integrated circuitry, and batteries.

Solar cells could apparently be produced with a multitude of different technologies, all respondents having their own preferred choice, although Gravure being the most selected. Screen, Offset and Flexo are all being thought of as interesting or possible technologies to use. LEDs demands thin layers and higher resolution, to achieve good fill factor thin conducting lines is important, pin hole free layers are important for avoiding short circuits between layers. Screen printing is a commonly used method to print large area sensors, other relevant methods are Ink jet and Flexo.

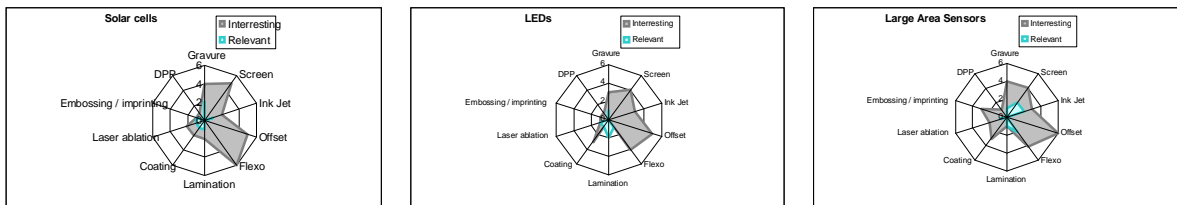


Figure 4. Preferred printing methods for producing solar cells, LEDs and large-area sensors.

The survey made indicates that screen printing is the second most relevant method after ink jet for producing displays although for the first generation EC displays it is the preferred method due to the availability of inks (PEDOT:PSS) and for the fact that the electrolyte need to be printed in a rather thick layer ($>20\mu\text{m}$ wet ink). For the second generation of pixel based displays ink jet gives the benefits of higher resolution and narrow line widths. Lamination is always going to be an important technology for protection and encapsulation or to introduce conducting and non conducting layers.

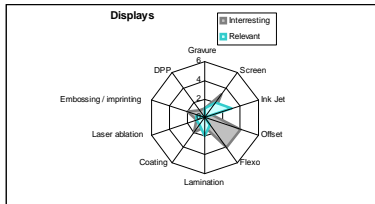


Figure 5. Preferred printing methods for producing displays.

6.2 Information processing

After collecting and processing the draft requirements for R2R manufacturing equipment the work with the final requirements was initiated. The project partners considered that the definition of the final requirements should also be supported by a proven and consistent methodology. In search for such approach a method known as Quality Function Deployment (QFD) was identified. The QFD is a method for translating subjective and often qualitative end-user demands into measurable and prioritised engineering targets.

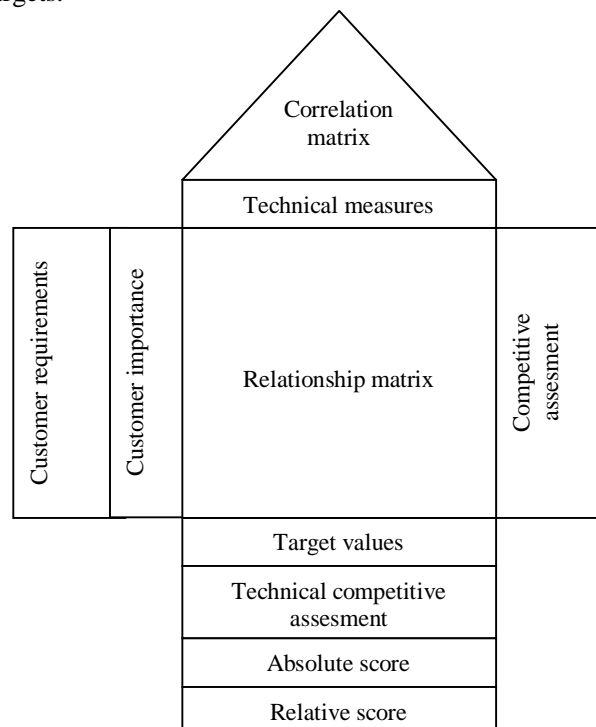


Figure 6. Schematic and components of a House of Quality matrix.

The QFD matrix is called House of Quality (HOQ). It is a structured template and analysis tool for developing and interconnecting specifications at different levels of detail. A typical QFD deployment process involves four interconnected phases. In each phase one or more matrices are prepared to help determine and communicate critical planning and design information. In product planning phase end user requirements are translated into functional technical requirements to meet them. In part deployment phase functional technical requirements are translated into key part characteristics or systems. Further, process planning phase involves identification of key process requirements necessary to achieve key part or system characteristics. Finally, process control phase establishes critical process control methods and parameters to develop appropriate process control plans, maintenance plans, and training plans to control operations.

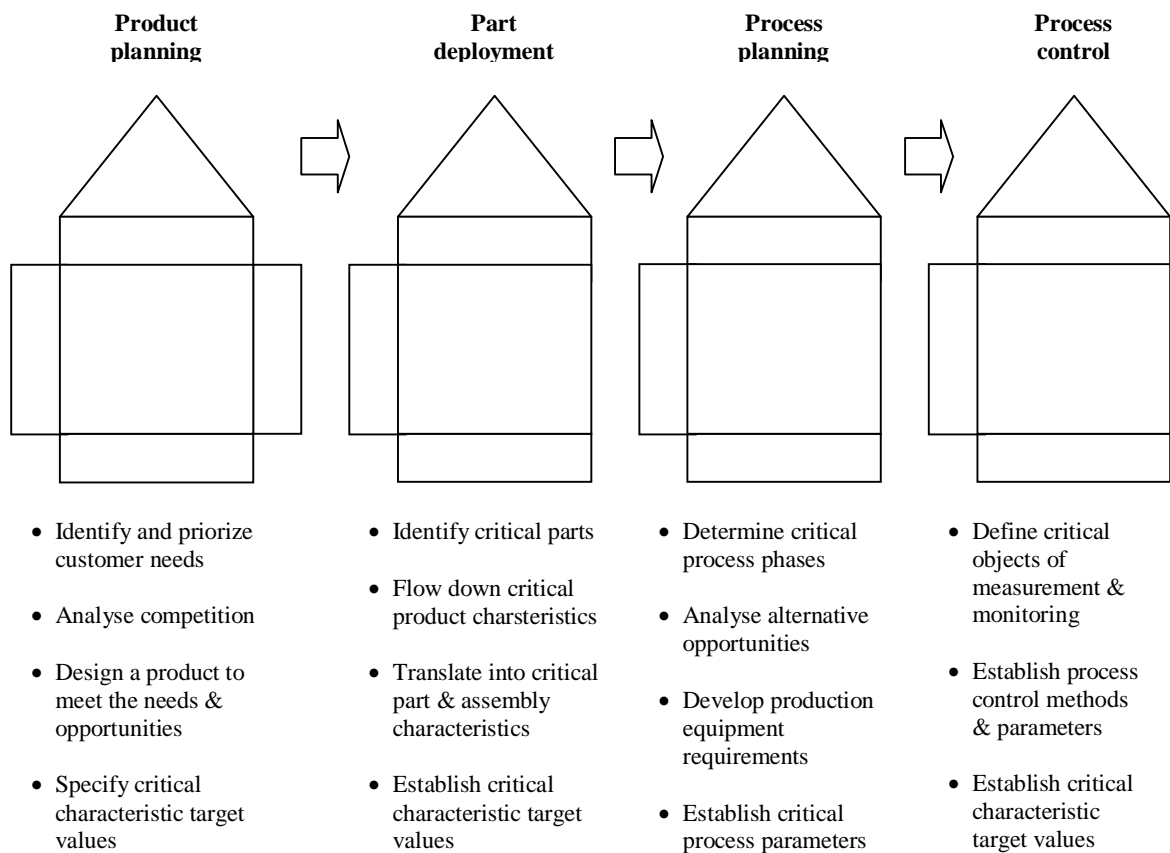


Figure 7. Phasing of QFD deployment process.

During the implementation of work reported in deliverable D1.2 QFD matrices were used in supporting workshop sessions as well as in gathering and organising the information. The greatest benefit of adopting the QFD approach was our improved ability to interconnect individual requirements into system level concepts for roll-to-roll manufacturing equipment.

7 Acknowledgements

The Prodi deliverable D1.2 has been produced in collaboration with companies, research institutions, colleagues, experts and EU officials, who provided information, materials, data and suggestions or helped in organising the Prodi meetings and/or workshops. Special thanks should thus be addressed to all.

8 Appendices