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PRODI

WP1 Printed display manufacturing requirements

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2009-10-09

Report no: acr027832

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Report's title

PRODI WP1 Printed display manufacturing requirements

Summary

Printed displays are made with a number of technologies such as thermochromic, 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 ether 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 ±5 µm. Curing times must be lower than 3 seconds for water based inks and the conductivity in conducting lines less than 10 Ω/□.

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.

Contents

1 Printed displays technology overview

1.1 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 thermochromic, 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 electrochromical 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.

1.2 Scope

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.

1.3 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.

1.4 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, lithe 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.

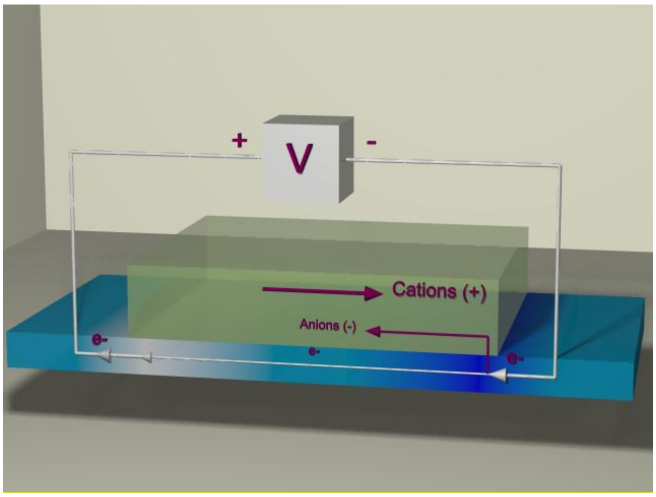


Figure 1. Ion transport in an EC display.

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 100µm is left between the rows of pixels to print conducting lines and transistors.

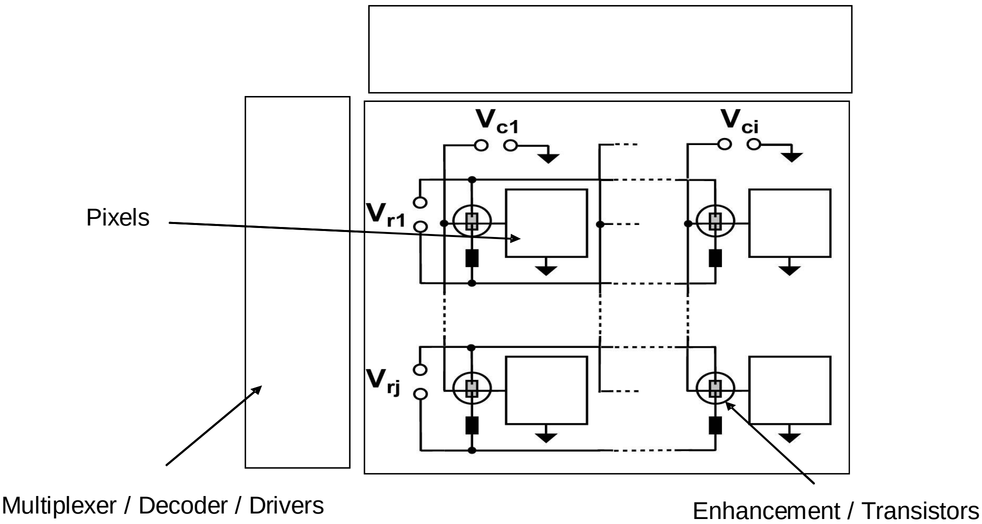
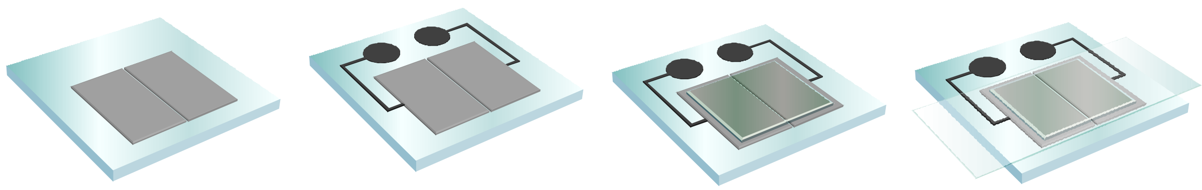


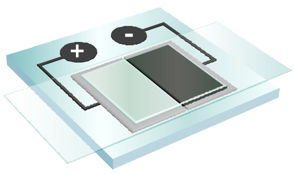
Figure 2.Schematic view over pixel display with enhancement transistors on each pixel.

1.5 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 ≤ 10 µm. 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 (≤ 30 µm) 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 pattering 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.



1) Printing of electrodes 2) Printing of conducting lines 3) Printing of electrolyte 4) Encapsulation



Activated by 1.5 to 3 V

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.

2 EC display manufacturing requirements

2.1 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 °C during less then 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 then 10 µm.

2.2 Production process requirements and challenges

2.2.1 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. Absorbation 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

2.2.2 Electrode printing and curing

2.2.2.1 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

2.2.2.2 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.

Printing method	Advantages	Disadvantages
Flexography	- Thin layer - Low viscosity inks - Low nip pressure - Adjustable ink transfer	- Poor resolution and register - Excessive spreading
Gravure	- Thin layer - Low viscosity inks - High resolution - Adjustable ink transfer	- Solid tones reproduced via ink spreading - Ink transfer problems - Excessive spreading - High nip pressure
Offset	- Thin layer - No excessive spreading - High resolution	- High viscosity inks - Ink layer roughness - High nip pressure
Inkjet	- Thin layer - Low viscosity inks - High resolution - Non-contact	- Low speed - Nozzle clogging - Excessive spreading
Screen printing	- Commercially available inks - Low pressure - Thick layers à covers roughness	- High viscosity inks - Thick layers - Poor resolution

2.2.2.3 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 °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
- Low conductivity - Layer homogeneity and roughness - Thickness and resolution requirements	- Printing process optimization - Material development and ink formulation

2.2.3 Conductors and contact pads printing and curing

2.2.3.1 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	µΩcm
Register	30	< 5	µm

2.2.3.2 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 °C) is needed

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

Printing method	Advantages	Disadvantages
Flexography	- Thin layer - Low viscosity inks - Low nip pressure - Adjustable ink transfer	- Poor resolution and register - Excessive spreading
Gravure	- Thin layer - Low viscosity inks - High resolution - Adjustable ink transfer	- Solid tones reproduced via ink spreading - Ink transfer problems - Excessive spreading - High nip pressure
Offset	- Thin layer - No excessive spreading - High resolution	- High viscosity inks - Ink layer roughness - High nip pressure
Inkjet	- Thin layer - Low viscosity inks - High resolution - Non-contact	- Low speed - Nozzle clogging - Excessive spreading
Screen printing	- Commercially available inks - Low pressure - Thick layers à covers roughness	- High viscosity inks - Thick layers - Poor resolution - Screen blocking

2.2.3.3 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
- Low surface roughness, homogeneous layer -> high conductivity - Toxic solvents - Rather thick layer - Sintering in rather low temperatures -> high conductivity	- 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

2.2.4 Electrolyte printing and curing

2.2.4.1 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 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**

2.2.4.2 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	- cheap printing plates - low nip pressure - accurate and adjustable ink transfer	- thin layer
Inkjet	- non-contact (no pressure) - high quality -	- thin layer - low speed - nozzle clogging
Gravure	- high quality - high speed - adjustable ink transfer	- thin layer - expensive printing cylinders - solid tones reproduced via ink spreading - ink transfer problems - high nip pressure
Screen Printing	- thick layer - commercially available inks - low pressure	- medium speed

2.2.4.3 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
- Poor mechanical strength (low adhesion) - Thick layers	- Ink formulation and optimization

2.2.5 Encapsulation

2.2.5.1 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/m2 x d

2.2.5.2 Suitable deposition and drying methods

Table 13. Advantages and disadvantages of suitable deposition methods.

Printing method	Advantages	Disadvantages
Flexography	- Low nip pressure - Accurate and adjustable ink transfer - Cheap printing plates	- Poor resolution - Poor chemical resistance - Low ink viscosity and thin layer
Gravure	- High resolution - High printing speed - Superior chemical resistance - Adjustable ink transfer	- Low ink viscosity and thin layer - High nip pressure - Solid tones reproduced via ink spreading - Ink transfer problems
Screen printing	- Thick layer - Low printing pressure - High solids content and viscosity	- Poor resolution - Chemical resistance - Low speed
Coating	- Thick layer - Smooth and homogeneous layer	- No patterning
Lamination	- Standard process for roll to roll manufacturing - No step drying needed - High speed	- No patterning

2.2.5.3 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**
- Development of printed encapsulation with low permeability	- Material development and ink formulation - Process optimization

3 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 Ω/□.	< 10 Ω/□.
Registration	Better than ± 50 µm between layers.	Better than ± 5 µm 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 µm height excluding substrate.	< 10 µm 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 °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 References

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