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## PRINTED ELECTRONICS AND DIAGNOSTICS PRODUCTS – PRINTOCENT DESIGNER’S HANDBOOK

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6.1.3 Transparent Conductors

TRL: 6 - 8

Author: Marja Vilkman, VTT

Introduction
Applications where flexible transparent conductors are needed include e.g. printed solar cells, OLEDs and touch screens. Currently, the main transparent electrode material in printed electronics is indium tin oxide (ITO), sputtered on a polyethylene terephthalate (PET) foil. However, new methods or materials to replace ITO are studied extensively, mainly due to the increasing price of ITO and its brittleness, which naturally is a severe disadvantage in flexible devices.

As summarized in Figure 1, transparency does not necessarily require invisibility: e.g. in solar cells, also visible electrode grids are accepted if the overall transparency remains high enough. The visible structures can be produced with simple and fast roll-to-roll (R2R) techniques but require an additional conductor, usually PEDOT:PSS, on the grid to provide sufficient conductivity between the otherwise highly conducting structures. It has been shown that if the distance between the grid lines is larger than 10 µm, an additional conductor is needed to reduce the lateral resistance [1].

On the other hand, in applications like OLEDs, the electrodes should be invisible to the eye. Invisible electrodes can though consist of grids or non-transparent materials, if the line width of the grid is too small to be seen with eye, i.e. preferably 1 µm or less. These structures require special materials or techniques, which are slower or more complicated when compared to direct printing, but the advantage is that no additional conductor is needed on the structures.

Figure 1. Summary of the possible transparent electrode categories.
Several solutions to replace ITO have been presented in literature, see e.g. [2] and [3]. Suitable materials include metal nanowires [4],[5], printed metal nanoparticles [6],[7],[8] with varying line width (1-100 µm, depending on the method), graphene or carbon nanotubes with grid electrodes [9],[10] or pure graphene, deposited by chemical vapour deposition [11],[12].

In addition, commercial producers for transparent electrodes are starting to appear: the methods include e.g. rolling mask lithography (www.rolith.com), which can produce sub-micron metallic grid patterns, printable silver nanowires (www.cambrios.com), micron-sized metal mesh sheets, based on nanoimprinting techniques (www.svgoptronics.com), and R2R direct dry printing of carbon nanobuds (www.canatu.com).

The following chapters describe techniques to prepare transparent conductors in more detail, focusing on methods, which are currently used or developed at VTT. The methods are also summarized in Figure 2, showing examples of grid electrodes in different sizes and fully covered electrodes.

![Figure 2. Examples of transparent conductor technologies, which are currently developed at VTT.](image)
Grids based on R2R evaporation
Evaporation is not a high-speed process but it is suitable for coating of flexible substrates in a R2R environment. The most important advantage of evaporated metallic structures is high conductivity (low sheet resistance) as thin layers, which allows low layer thickness (30-50 nm) for the electrode. The low layer thickness is essential to avoid short circuits in the device, since some of the printed layers on the electrodes might be less than 50 nm thick.

VTT uses two evaporation-based processes, which are optimized to produce at the minimum 20-50 µm wide conducting patterns: one is based on lift-off and the other on etching. In contrast to e.g. nanoimprint lithography, both of these methods are also suitable for large patterns, which enable preparation of both narrow and large metallic patterns in one printing step.

The lift-off process consists of three stages: resist printing by flexography to provide the (negative) pattern of the electrodes, evaporation, and lift-off – all in a R2R process. 20 µm wide silver lines have been demonstrated with this process in the printing direction.

The etching process utilizes an etching ink, which is printed on the evaporated metal layer. The ink etches the desired areas away and the used ink is washed off in an ultrasonic water bath, which is included in the same printing line. The best method for the etching process is screen printing, since it allows high wet thickness for the etching ink, enabling complete etching in one printing run. Commercial etching pastes for screen printing do exist (e.g. HiperEtch by Merck) but VTT has also developed an own ink formulation to etch Ag, Cu or Al, and the process has been demonstrated in a flatbed screen printing process with 50 µm resolution and in rotary screen with 100 µm resolution. The etching quality with this process is not depended on the printing direction.

Figure 3 shows optical microscope images of silver patterns, produced with etching and lift-off. Photographs of the same samples are shown in Figure 4, which illustrates that small and large patterns can be produced in the same printing step.

Figure 3. Optical microscope images of silver lines, which have been patterned by etching with flatbed screen printer (left) or by lift-off in a R2R process (right). The etched lines are 50 µm wide and the line produced with lift-off is 20 µm wide.
Direct printing of grids with standard techniques

The simplest and fastest method to produce transparent grid electrodes is to print the structures with a metallic nanoparticle ink. The resolution of this process is limited to 20-30 µm lines with standard flexo or inkjet printing processes in the best case. However, such narrow patterns require that the ink and the printing parameters are carefully optimized. Figure 5 shows examples of inkjet and flexo printed silver nanoparticle ink.

Figure 5. Examples of inkjet (left) and flexo (right) printed lines using a silver nanoparticle ink. The scale bar is 50 µm in both images.

Most of the printed electronics applications require that the electrode layers are as thin as possible, preferably 200 nm or less, while maintaining sufficient conductivity. In addition, the printed lines should not contain spikes, since they can easily lead to short circuits. Also short curing times (few minutes or less) at low temperatures (< 150 °C) are necessary. It is not self-evident to fulfill these requirements, but it is possible if all of the parameters (ink formulation, printing speed, drying conditions, substrate pre-treatment etc.) are correctly selected.
6.7 Printed Battery

TRL: 9

Author: Eero Suomalainen, Enfucell Oy

Introduction
Enfucell SoftBattery is an electro-chemical electricity source. It is a primary (i.e. non-rechargeable) battery utilizing the well-known chemistry; manganese dioxide – zinc chloride – zinc.

The battery contains relatively inexpensive ingredients and is manufactured using screen printing technology. In addition the battery is designed in a way that enables manufacturing with roll-to-roll process.

The basic properties of SoftBattery

- Thin
- Flexible
- Scalable in size, shape and voltage
  - Higher voltages are achieved by serial connection of cells within the same casing.
- Low manufacturing costs
- Inexpensive raw materials
- Environmentally friendly
  - Does not contain mercury, cadmium or lead

Applications
Enfucell SoftBattery is best suited for applications that require low power, such as

- RFID tags
- Microsensors
- Pharmaceutical and cosmetic patches
  - Functional packaging

Figure 1. Examples of SoftBattery products
### Structure

*SoftBattery* is composed of several layers that are produced by screen printing. Figure 2 reveals the layers from top to bottom:

- Casing
- Zinc (Zn) anode
- Paper separator with ZnCl₂ electrolyte
- MnO₂ cathode
- Substrate

The substrate is typically PET foil. In the optimum case the battery is printed on the same substrate with the electronics.

![Figure 2. Enfucell SoftBattery structure](image)

### Properties

#### Table 1. Printed battery properties

<table>
<thead>
<tr>
<th></th>
<th>SoftBattery Mini 1.5V</th>
<th>Generic values for a 1.5 volt cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.7 mm</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Dimensions</td>
<td>36 x 46 mm</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>0.90 g</td>
<td>~50 mg/cm²</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>1.5 V</td>
<td>1.5 V</td>
</tr>
<tr>
<td>Capacity</td>
<td>18 mAh</td>
<td>~4.0 mAh/cm² (cell active area)</td>
</tr>
<tr>
<td>Nominal current</td>
<td>0.2 mA</td>
<td>0.01 C (40 μA/cm²)</td>
</tr>
<tr>
<td>Internal resistance</td>
<td>~150 Ω</td>
<td>~600 Ω·cm²</td>
</tr>
</tbody>
</table>

### Discharge

Figure 3 shows discharge curves of *SoftBattery Mini 1.5V* with discharge currents 0.2, 0.5 and 1.0 mA. The X-axis is capacity instead of time, which allows direct comparison between various loads. The nominal capacity is well achieved with the nominal current 0.2 mA. A higher discharge current results in reduced capacity.

Cut-off voltages 0.9 and 1.2 volts are marked in the chart to indicate the impact in the useful capacity.

Both the decreasing voltage and the increasing internal resistance towards the end of the discharge are typical for a battery with this chemistry.
Another way to look at the discharge reality is in Figure 4, with coordinates capacity and current. The following factors have an impact in the achievable capacity from the battery. Change towards the green curve is expected if e.g. the battery is fresh or has been properly stored.

<table>
<thead>
<tr>
<th>Negative impact</th>
<th>Positive impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry conditions</td>
<td>Freshness</td>
</tr>
<tr>
<td>Extreme temperatures</td>
<td>Better materials</td>
</tr>
<tr>
<td>Repeated bending</td>
<td>Good connection</td>
</tr>
<tr>
<td>High cut-off voltage</td>
<td></td>
</tr>
</tbody>
</table>

Operating conditions

The operating temperature of Enfucell SoftBattery is -35 ... +60 °C. For short periods the upper limit can be exceeded e.g. during post-processing of a device.

A rule of thumb in chemistry dictates that the speed of chemical reaction doubles with temperature increase of 10 degrees. Consequently, at the upper extreme of the temperature range one can expect shortening of shelf life and service life due to accelerated self-discharge.

Figure 3. Enfucell SoftBattery Mini 1.5V discharge curves

Each curve crosses X-axis at the corresponding short circuit point (V/R, 0). They coincide far left where the load current is small.
6.9.4 Resistive Touch Screen

TRL: 7

Author: Markus Tuomikoski, VTT

Introduction

Touch screen technology is growing across many different applications including consumer electronics, commercial products and industrial equipment. There are many different touch screen technologies, and they are categorized into several categories e.g. resistive, capacitive (surface and projected), infrared, optical touch, acoustic wave, and others. The choice of technology is highly depended on application and size requirements. Resistive technology dominates markets shipments due to its low cost, and projected capacitive is ranked in second position.

Table 1. Comparison of different touch technologies

<table>
<thead>
<tr>
<th></th>
<th>Resistive</th>
<th>Capacitive</th>
<th>Optical</th>
<th>Infrared</th>
<th>Acoustic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Touch resolution</td>
<td>very good</td>
<td>good</td>
<td>good</td>
<td>poor</td>
<td>good</td>
</tr>
<tr>
<td>Cost</td>
<td>low</td>
<td>medium</td>
<td>medium</td>
<td>high</td>
<td>medium</td>
</tr>
<tr>
<td>Display size</td>
<td>1 - 20&quot;</td>
<td>2 - 20&quot;</td>
<td>19 - 100&quot;</td>
<td>20-150&quot;</td>
<td>10 - 42&quot;</td>
</tr>
<tr>
<td>Input methods</td>
<td>stylus / finger</td>
<td>finger / stylus</td>
<td>anything</td>
<td>finger</td>
<td>finger</td>
</tr>
<tr>
<td>Notes</td>
<td>durability challenges, touch registration requires force</td>
<td>for big screens</td>
<td>problems in sunny conditions</td>
<td>requires forceful touch</td>
<td></td>
</tr>
</tbody>
</table>
VTT is developing fully flexible, large area and printable resistive touch sensor technology. The resistive touch sensor structure includes two layers of patterned resistive substrates, such as ITO coated PET, and an insulating spacer layer with air gap in between.

R2R manufacturing begins with the patterning of ITO-PET foils using the paste etching process. This is followed by the rotary screen printing of commercial silver paste for conductive wirings and a dielectric paste for an insulating spacer layer. In addition, the layers are cured through the hot air dryers after each printing process. The final process step includes the foil cutting and the foil lamination using an suitable adhesive.

The working principle of analog touch sensor in short, when pushing on the upper substrate with a finger or stylus, the two conductive resistive substrates are connected, and the electrical current goes through the point of contact. The touch position is detected and calculated by the controller integrated circuit.

The advantages of VTT’s large area sensing technology include:

- Thin and flexible form factor
- Compatibility with standard communications protocols such as NFC, RFID, ZigBee and WLAN
- Integration into surfaces with printed graphics and different textures, enabling attractive user experiences
- The use of hybrid combinations of various sensing and communication technologies

Figure 2. Resistive touch sensor structure
7.3 In-mould Labelling

Author: Sami Ihme, VTT

Integration of flexible LED foils to product structures
In-mould integration (IMI) technology enables seamless integration of functionalities like LED illumination, control electronics, sensors (such as capacitive touch), as well as energy harvesting, power sources and power storage into novel 2.5D/3D applications. In-mould integration functional foils are over-moulded with hard plastics or flexible elastomers, thus integrating functionalities as part of the plastic product. The method enables highly compact and robust product structures with elastomers giving a bendable product and new design freedom in terms of the location of functionalities and shape of device. In addition, high efficiency light coupling between the LEDs and light guides can be obtained. VTT has also invested in a new ENGEL Victory120 2-shot injection moulding machine with R2R foil feeder system (Figure 1) which can be used for IMI R&D, pilot runs and up-scaling.

Over-moulding design guidelines
Structure of an overmoulded system can be unbending, bending or stretchable depending on parts geometry and material selection.

Figure 1. Injection moulding machine with a foil feeder in PrintoCent pilot factory.
Common design guidelines for thermoplastic part geometry, injection moulding tooling and processing are valid. However some overmoulding specific design guidelines and practices are important to be considered.

If electronics foil is formed in over moulding process or in a final product, exact strain and specific elongation at break (or yield) of the component and conductor material has to be specified. This set the maximum limit for deformation and also limit for the minimum bending radius.

**How about temperature shock to sensitive components?**

Despite of high processing temperatures during the injection moulding process, the time that functional components on the foil are exposure to high temperature is relatively short (order of seconds). Therefore, the temperature shock will not harm the sensitive – even organic materials containing components. Also any protective layer between will ease the risk for temperature shock.

**Over-moulding material selection**

Overmoulding materials are polymer based thermoplastic and thermoplastic elastomer resins. Melting and solidifying of a thermoplastic material is reversible process. A thermoplastic material is injected with heat and pressure into a mould where the printed electronics foil is pre-inserted.

A foil has to be thermoplastic material to build-up the adhesion with an overmoulding thermoplastic resin in overmoulding process. Typical foil materials are polyethylene terephthalate (PET) and polycarbonate (PC) that have good adhesion with thermoplastic injection moulding resins like polyesters (PET, PBT and PC) and polyurethane (TPU). As a rule of thumb, same polymers or polymers with similar polarity have good chemical compatibility.
### Table 1. Adhesion between some transparent foils and overmoulded polymers

<table>
<thead>
<tr>
<th>Film material</th>
<th>Overmoulded polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC1</td>
</tr>
<tr>
<td>PC</td>
<td>++++</td>
</tr>
<tr>
<td>PET1</td>
<td>+</td>
</tr>
<tr>
<td>PET2</td>
<td>++</td>
</tr>
<tr>
<td>PET3</td>
<td>+</td>
</tr>
<tr>
<td>PET4</td>
<td>++++</td>
</tr>
<tr>
<td>PEN1</td>
<td>++++</td>
</tr>
<tr>
<td>PEN2</td>
<td>+</td>
</tr>
</tbody>
</table>

- ++++ very good adhesion > 1.5 N
- +++ good adhesion > 1 N
- ++ weak adhesion > 0.5 N
- + very weak adhesion > 0.2 N
- - no adhesion

**Mould design and component positioning**

A wall thickness has to be more than component height in an overmoulded embedded structure. Minimum average wall thickness of 1mm is recommended. Other wall thickness related conventional injection moulding design rules are valid that mainly depends on the rheology of an overmoulding resin. Component distance of >10mm from the gate is recommended. Sensitive components should be located as far as possible from the gate.

**I/O Interface**

Connector interface has to be out of the moulding or on the free surface. That requires precise cut-off for a connector output and a proper shut-off in a tooling. In some cases thin conductor lines can be output in a tool parting line even there is always a high risk for conductor failure due to the high clamping force.

**Process setting**

Overmoulding process setup procedure is similar like in conventional injection moulding process. There is no need to compensate the metering with thin foil type of elements. Metering compensation is needed for components with higher volume. Injection pressure can be increase e.g. 30% with high volume components.
8.3 Physical Sensor Platform

Author: Juha Häkkinen, University of Oulu

The operation of the printed physical sensor shown in Figure 1 is based on the parallel circuit formed out of two basic electrical components, namely, an inductor coil and a capacitor. In our case the inductor and the capacitor forming the so-called parallel resonator are manufactured by screen printing on a PET-type plastic sheet, for example.

The frequency of oscillation $f_0$ depends on the inductance $L_T$ of the inductor and the capacitance $C$ of the capacitor by the following equation:

$$f_0 = \frac{1}{2\pi\sqrt{L_T C}}. \quad (1)$$

Similarly, the quality factor $Q$ of the sensor can be calculated as follows:

$$Q = \frac{f_0}{\Delta f} = \frac{1}{Q_L + \frac{1}{Q_C}},$$

where $\Delta f$ is the bandwidth of the sensor and $Q_L$ and $Q_C$ are the quality factors of the sensor inductor and capacitor, respectively. The first part of equation (2) is convenient for sensor interrogation and the second part is convenient for hand design, as will be shown below.
Sensor interrogation: by measuring the magnitude response of the sensor according to Figure 2, equation (1) and (2) can be used to find out sensor reading.

![Simple circuit model of the sensor and its frequency response](image)

Figure 2. Simple circuit model of the sensor and its frequency response

In case of a humidity sensor, for example, when the humidity around the capacitor increases, the capacitance increases also, because the relative permittivity of water absorbed by the capacitor’s insulator is about a hundred times higher than that of air. Therefore, the capacitance is proportional to the amount of water in the insulator. This moisture sensitive capacitor is now part of a parallel resonator, the frequency of oscillation is also made proportional to the humidity. It is important to emphasize that the sensor is able to measure the humidity of a large variety of materials, as long as the material under observation is placed to the close physical proximity of the capacitor.

**Inductance calculation**

The total inductance of an N-turn planar spiral inductor coil (Figures 3 and 4) can be calculated as follows:

\[
L_T = L_0 + M_+ - M_- [\mu H], \text{ where (3)}
\]

\(L_T\) is the total inductance, \(L_0\) is the sum of self-inductances of all straight segments, \(M_+\) is the sum of positive mutual inductances, and \(M_-\) is the sum of negative ones.

The self-inductances of a rectangular cross-section conductor can be obtained using the following equation:

\[
L = 0.002l \left[ \ln \left( \frac{2l}{w+t} \right) + 0.50049 + \frac{w+t}{3l} \right] [\mu H], \text{ where (4)}
\]

\(w, t, l\) are the segment’s width, thickness, and length in cm, respectively.

The mutual inductance is the inductance that results from the magnetic fields produced by adjacent conductors. The mutual inductance is positive when the directions of the current along the conductors are in the same direction, and negative when the directions of currents are in opposite directions. The mutual inductance between two parallel conductors of equal length is a function of the length of the conductors and of the geometric mean distance between them.

Continues for 3 more pages
8.6 Flexible Large Area Luminaire

Authors: Markku Kylmänen, Neficon Finland Oy
Jukka-Tapani Mäkinen, Kari Rönkä, VTT

Target specification
VTT Falaisin is a large-area 2m x 0.2m luminaire demonstrator utilizing commercial warm/neutral white LEDs in a flexible substrate. The luminous flux performance is around 300 lx at table level (1-2m distance). The VTT Falaisin has a remote (RF) controllable PWM dimmer connected to a 24V DC power supply. In following, the design flow progress and related alternatives and final selections have been presented.

Electrical design of single LED string
System electrical design starting point was luminosity target 300 lx at 1m distance. Performance of commercially available LED components were initially screened and according to optical simulations ~60 LEDs at 50mA should give the targeted luminous flux/m². Therefore, 20 x 6 LED strings on 0.2m x 2m panel size were selected, leading two alternative choices for assembly a) 120 LEDs heading for maximum luminosity performance and b) assembling only every other string with 60 LEDs.

Figure 1. System building blocks

Figure 2. Single LED string electrical design / characteristics
System was designed to operate with constant 24V supply. One LED string current level was targeted to be 50mA. Fixed resistors were used for current setting. Current setting resistance of around 110 Ohm was needed to get 50mA per LED string. This was implemented with two 56R resistors due to need of symmetrical design and effective heat distribution.

Drawback of using resistors is the high power dissipation (<300mW) in resistors, leading to poor system efficiency around 75%. Also any potential short circuit in one LED will increase the current level in that string by 50%. Alternative and better solution for the efficiency and fault tolerance would have been using current mirror for current setting. With current mirror solution efficiency would be around 87%, and in case of a short circuit in one LED there would be no impact on string current level. Also current mirror solution allow to use of 7 LEDs in series in one 24V string as in the resistor solution only 6 LEDs can be designed. This alternative solution was dropped this time due to increased complexity and schedule pressure.

Summary of electrical characteristics of single 6-LED string are presented in table below with 56R +/-5% and LED forward voltage 3.0V +/- 100mV. Estimated average 0.5V voltage drop in power cabling and routing in LED panel included.

Table 1. Electrical characteristics of single 6-LED string

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pdiss [W] @ R [W]</th>
<th>System Efficiency [%]</th>
<th>Current [mA]</th>
<th>Overall current tolerance [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single LED string</td>
<td>1,15</td>
<td>0,27</td>
<td>&lt;75</td>
<td>49</td>
</tr>
</tbody>
</table>

Formula (1) can be used to calculate LED string current at other resistance values.

\[ I = \frac{(24V - 6V_f)}{2R} \]  \hspace{1cm} (1)

where

\[ I = \text{string current} \]
\[ V_f = \text{Led forward voltage} \]
\[ R = \text{current setting resistor resistance} \]

LED forward voltage variation will cause mismatch between the strings. A compromise has to be made between the string current mismatch and the power wasted in the current setting resistors. In this case 25% of the supply voltage is used in the resistors. Another cause for current mismatch can be the voltage loss in the power rails. Since the luminaire is normally powered from one end, the LEDs in the other end will get lower voltage. Wide supply rails or high conductivity materials are needed for low resistance rails.
Schematic and layout
Design consists of 200mm x 203,2mm modules having two LED strings. A schematic of one module is presented in figure 3.

![Schematic of one module](image)

Figure 3. Schematic of one module

The layout which was sent to manufacturing is presented in figure 4. It consists of 3 modules so that length is optimized for manufacturing line repeat length. Layout of one module consists of two LED strings, power rails and 1cm x 1cm contact areas for power supply and bonding areas for resistors and LEDs. Distance between each LED string is 101,6mm. Plus and minus markings can be used as fiducials in VTT automated assembly.

Manufactured design (LED panel) on a flexible circuit substrate is continuous i.e. there will be no discontinuity in power rails. End product can be cut to arbitrary length between each LED string. Bonding / soldering pad designs are done so that strings can be assembled or left un-populated.

All copper conductive routing except in the contact pad areas is covered by white protective mask layer. The mask overlaps the copper areas by 0,5mm. In the edges the mask is extended all the way to the edge.

![Design layout sent to manufacturing](image)
10. Cost Considerations

Author: Kari Rönkä, VTT

Background
Running a Roll-to-Roll printing line with 5 meters per minute speed, would result of a functional roll length of 7 km within 24 hours. Low-cost manufacturing and functionalities have been once major value proposition of printed intelligence. However, concrete cost calculations and indications are still quite limited. Costs calculation of printed electronics materials, processes, components and systems is not a straightforward task. Several factors will have a major impact to the absolute and relative cost structure. Material costs depends, especially in the early stage of the market entry, on the pricing model of R2R costs, availability and delivery batch sizes, raw material price changes as well as if the same material is used also to other industry. Different printing processes have different tooling costs and printing line costs depend on if a specialised or flexible printing line can be used. In the system level the product specification performance and reliability requirements determine the selected materials, manufacturing and testing process, which will have a major impact to the final product cost structure. As de facto, printed functionalities manufacturing gives opportunity to scale-up to huge manufacturing volumes, the product yield will have a major impact on the final cost structure. Therefore, understanding the impact of layout design rules, material and process variations and integration level to the production yield will become crucial. It should be also realised that in the beginning of the technology development and in the ramp-up phase, the ultimate cost-efficiency value proposition cannot necessarily be met, but high enough production volumes need to be reached. However, PrintoCent pilot factory provides a unique environment to learn and develop factors impacting the production yields and cost structure. In this chapter, some indicative cost considerations will be discussed.

Cost considerations

Materials costs

Substrates
Several requirements will affect the substrate material and grade selection: temperature stability, mechanical properties (tensile strength etc. bending stiffness, impact etc.), dielectric strength, chemical resistance, surface roughness etc. Also, the thickness of the substrate, the width and length of the roll will have an impact.
10. COST CONSIDERATIONS

- It is recommended to use fully heat stabilized film with very low shrinkage. A base line for a 500 m PET roll (300 mm wide, 125 um thick) is 500 € (2.8 €/m²).
- Conductive ITO-PET substrate is needed e.g. for OPV, OLED and transparent touch. Indium Tin Oxide-layer sputtered on PET foil increases the price considerably. Base line for 300 m ITO-PET roll (300 mm wide, 125 um thick) is about 2000 € (22€/m²).
- Typical materials used for hot embossing, such as PMMA and COC, e.g for 250 m roll (300 mm wide, upto 375 um thick) about 1200 € (16€/m²).

**Conductive inks**
Typically cheapest micro particle (PTF) silver ink prices can be down-to around 1000 €/kg in bigger quantities. In smaller quantities and more specific inks (printability or special properties like formability) the price can rise up to 2000 €/kg. As the conductive inks consist typically about 70 %-w from silver, the global silver price changes will impact directly also Ag ink prices. There are many nanoparticle Ag ink suppliers emerging to the market. The nanoparticle inks cost per kg have a very wide range between 3000 and 10000 € /kg in small quantities. Some suppliers have estimated that they can produce Ag ink cost about 2000 €/kg could be reached. As Ag is a good conductor, the conductivity is better compared to thin film. It is, and therefore, thinner can be used. It should be noted that less silver volume is needed which is a benefit in expectation on emerging copper inks and value proposals down to 75 €/kg has been given. When using printed silver, the cost will be mainly impacted by the coverage of the printed area versus the total area. When the coverage is low, additive printing method is cost efficient compared to the subtractive etching. As a comparison, prices down-to 2.5 € / m² (Aluminium /PET) substrates can be achieved with etching process in high volumes.

Silver ink cost can be estimated as follows:

- Ink cost per kg: Cost(Ink) = 1500 €/kg (estimation)
- Layer dry thickness: t = 10 µm
- Density (silver ink) = \( \rho(\text{Ag}) = 2.65 \text{ g/cm}^3 \) (ink dependent)
- Solid content = Solid (wt) = 75 %
- Dry volume of the printed/cm² ink \( V(\text{dry}) = t \times 1 \text{ cm}^2 = 1 \text{ mm}^3 \)
- Ink consumption in mass/cm² = Ink (mass) = \( V(\text{dry}) \times \rho(\text{Ag}) / (\text{Solid (wt)} \times 1 \text{ cm}^2) = 3.53 \text{ mg/cm}^2 \)
- Cost/m² per print area = Cost(area) = Ink (mass) \times Cost(ink) = 53 €/m²
- Coverage e.g. 10 %
- Cost per m² (10 % coverage) = 5.3 €/m²

**Other typical inks:**
- dielectric inks about 1000 €/kg
- resistive inks about 3000 €/kg
- ITO- etching paste (screen printable) about 400 €/kg

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