Saarland University
Faculty of Natural Sciences and Technology I
Department of Computer Science
Master's Program in Visual Computing

Master's Thesis

Fabrication and Control of Flexible Thin-Film Touch-Displays

Michael Wessely

mwessely@mpi-inf.mpg.de
Visual Computing

Supervisor:	Dr. Jürgen Steimle
Reviewers:	Dr. Jürgen Steimle
	Prof. Dr. Antonio Krüger

Abstract

This master's thesis presents a digital fabrication pipeline that allows to create customized flexible displays based on thin-film electroluminescence. The fabrication is rapid and inexpensive even in a low volume production, which makes it perfectly suitable for print shops or even a home studio. We demonstrate how to print on various flat materials like paper, foil, leather and wood. The displays are ultra-thin ($\approx 120\mu m$) and can be designed as individual segments or even as a passive matrix display. Thereby, they are extremely flexible, bendable, rollable and even foldable. The designer can choose from a wide palette of different colors and create custom shaped displays. Moreover, we contribute a sensing framework that allows to use the internal structure of a display for a variety of sensing techniques making it a completely interactive device without adding any additional sensing layer. We demonstrate this technique with integrated touch sensing. To show the usefulness of this technology we implemented five application cases relevant in the fields of ubiquitous, mobil and wearable computing.

Acknowledgment

At this point I would like to use the opportunity to express my gratitude to several people that supported me in writing this thesis.
First of all I would like to thank Dr. Jürgen Steimle for offering me the possibility to work in this fascinating area of Human-Computer-Interaction within the Embodied Interaction group and giving me the opportunity to experience this creative and stimulating scientific environment. Another greatly inspiring person is Simon Olberding, whom I would like to express my special gratitude to for advising my thesis and spending hours in fruitful discussions during the late evenings in the lab. Moreover, I want to thank the many current or former members of the embodied lab. In particular, I want to thank Martin, who brought up many inspiring thoughts about on skin interaction but also has this irreplaceable sense of humor, which made the time in the lab always joyful. Of course, I also want to thank my fellow master student colleges Nisa, Niz and Sergio, who shared so much time with me during studies.

Last but not least, I want to thank my family for supporting me in every situation. They always meant a lot to me and I am very happy to have such a good relationship to them.

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1 Introduction

1.1 Motivation

Printing technologies are one of the cornerstone accomplishments of humanity leading to the information age we live in today. Many advances in graphic printing technologies over the past century allow to print products in high quality, in large volumes, rapidly and inexpensively.

These print products are nevertheless static and cannot depict dynamic content. Modern technologies are nowadays able to print electronics by using functional inks instead of colored inks. This enables the fabrication of flexible and very thin functional devices and HCI prototypes. The implementation of interactive components on static prints on thin and flexible substrates has already been demonstrated[Kawahara u. a. 2014; Gong u. a. 2014; 2011; Rendl u. a. 2014; 2012; Le Goc u. a. 2014; Olberding u. a. 2013; Savage u. a. 2012]. While sensing input from such functional devices has been shown recently, providing additional dynamic output in terms of flexible and customizable displays, which are inexpensive and rapidly to print, has not been possible so far. Display technologies like OLED and electronic paper may offer the property of being flexible and thin, but they nevertheless need to be produced in a high-end print lab with expensive equipment and by experts. This makes it impossible for this technology to produce custom displays in low volume and in low cost.

In this thesis we will present a fabrication method and an electronic controlling concept to produce highly customizable and flexible displays. The displays are based on electroluminescence and are capable of a variety of sensing methods. Results of this thesis were published as part of a full paper publication at the ACM UIST 2014 conference, which was honored with a best paper award:

Simon Olberding, Michael Wessely, Jürgen Steimle:
PrintScreen: Fabricating Highly Customizable Thin-Film Touch-Displays
[Olberding u. a. 2014]

In the remainder of this document, we will present the following contributions:

1.) The contribution of this master's thesis lies specifically in investigating the print technologies for printed electronics and implementing a practical printing approach that can be performed even by laypeople with inexpensive equipment. The resulting displays are ultra-thin($\approx 120\mu m$), bendable, rollable and even foldable. A display can be designed in a specific shape with very high edge resolution(comparable to 250dpi printer resolution) or as a passive matrix display to visualize dynamic content with up 30 pixel per inch resolution in the manual fabrication process. The color of the displays can be adjusted during design-time. The designer can choose from a large palette of available colors and can realize arbitrary color segments or pixel. The brightness of display segments can be altered during runtime. Further on, it is possible to print on a large variety of materials like metal, stone, paper or wood, which opens up tremendous new possibilities for applications in the internet of things, wearables or embedded applications. Moreover, the displays can be used in unconventional shapes when folding them to 3D structures or fabricating adaptable shapes.

2.) We present a sensing framework, which allows to use the internal structure of a display for a variety of sensing techniques. While up to now, the large electro magnetic field that is created by the alternating current power supply, imposes a great challenge for capacitive sensing techniques, we present a novel approach to clear the display from any electric noise rapidly within nanoseconds. This method allows to perform touch or even proximity sensing within a short period of less than $< 2ms$. We show this functionality exemplary for integrated touch sensing.

1.2 Organization

After starting with an introduction and a content overview of this thesis in the first chapter, we will discuss the recent developments in flexible display technology and its applications in chapter 2.

Chapter 3 will deal with the physical background of this technology. This will shed light onto the quantum mechanical principles behind the luminesce effect. Later on, we will investigate the physical and the chemical properties of the light emitting phosphor as well as the electrical requirements to run the displays.

Details of the fabrication with silk screen printing will be discussed in chapter 4. After starting with an investigation of the design space of electroluminescent displays, we will present all necessary materials and tools for screen printing and discuss their properties. We conclude this part of the thesis with information on the necessary power supply, safety instructions and ways to connect printed electronics to a controller or the chosen power source.

Adding input capabilities to a display by motivating a sensing framework will be discussed in chapter 5. After introducing a time division sensing cycle, we will explain the principles behind the necessary circuitry to enable a flicker-free operation and to solve the problem of the large electric field generated by the AC power supply. Finally, we will evaluate this construction with capacitive touch sensing.

To show the practical benefits and possibilities of interactive, thin and flexible displays, we will present in chapter 6 five application cases that show their usefulness in the areas of integration with static print, wearables, interaction with a passive matrix display and integrating awareness information into the environment.

The last chapter will summarize the facts and insights that were found throughout the thesis.

2 Related Work

In this chapter, we present related research and recent advances in printed electronics, thin-film display technologies and their applications in Human-Computer Interaction. The subsequent body of work shows that easy and rapid fabrication of flexible displays has a manifold usage in many different areas of HCI.

2.1 Printed Electronics

A large amount of publications show the practical benefits and new opportunities for Human-Computer Interaction that are made possible by printed electronics.

While it is often desirable to equip a surface or a 3D object with touch input capabilities, the design and the wiring of such devices is often tedious. In general, there are three steps to take:

- define location, type and size of the touch area
- route a wiring from the sensor locations to a connector location
- connect a controller board and program the desired behavior to the touch areas

These steps often need to be performed by an expert, which lowers the practical usability for casual applications. Midas[Savage u. a. 2012] offers a framework to create such custom touch-sensitive surfaces. While the designer still needs to go over step one, the last two steps are performed automatically by the MIDAS system. It allows to place and auto-route touch panels on flexible substrates and controls them via a controller board. The final touch panel can be fabricated by cutting out copper plates, milling methods or even by printing technologies.

[Kawahara u. a. 2013] introduced an instant fabrication method of single layer circuits on paper-like materials. For this, an off-the-shelf ink-jet printer is used, whose cartridge is filled manually with a silver nanoparticle ink. It then prints conductive traces directly on coated paper or foil. This yields a fast and cheap circuit fabrication process that is well suited for rapid prototyping. Nowadays, even carbon-based inks are available, which allow to print transparent traces. Later work[Gong u. a. 2014; Kawahara u. a. 2014] uses this technique to create custom antennas and sensor panels capable of a variety of sensing modalities. These sensors can be printed within seconds and are fully functional without any additional curing steps.

Pyzoflex[Rendl u. a. 2012] presents a flexible sensor foil, which is able to detect pressure and temperature. The used layers are based on a piezoelectric material and are fabricated by screen printing. Recent work with piezoelectric sensors also allows to measure bending of a flexible surface[Rendl u. a. 2014]. Via a machine learning based interpretation of the printed bend sensor signals, FlexSense is able to compute the 2D topology of a A4 sheet continuously without any discrete shape states.

[Karagozler u. a. 2013] use printed electronics as an energy harvesting method, where users generate electric energy by touching, sliding or rubbing. The user rubs with a sheet of conductive foil or even bare handed over the printed electrode. The kinetic energy of the movement is transformed into electric energy by induction. The produced voltage can be recognized as a trigger signal or is even able to light up LEDs.

[Le Goc u. a. 2014] show a 3D finger and hand tracking device based on electric field sensing. A conductive thin film circuit is applied to a flexible foil, which can then sense changes in the electric field above the sensor. The electrodes are shaped by laser patterning of an ITO(Indium Tin Oxid) coated sheet. Alternatively, the sensor can also be fabricated by screen or ink-jet printing.

All presented technologies in this section are restricted to sensing without direct visual feedback.

2.1.1 Thin-Film Display Technologies

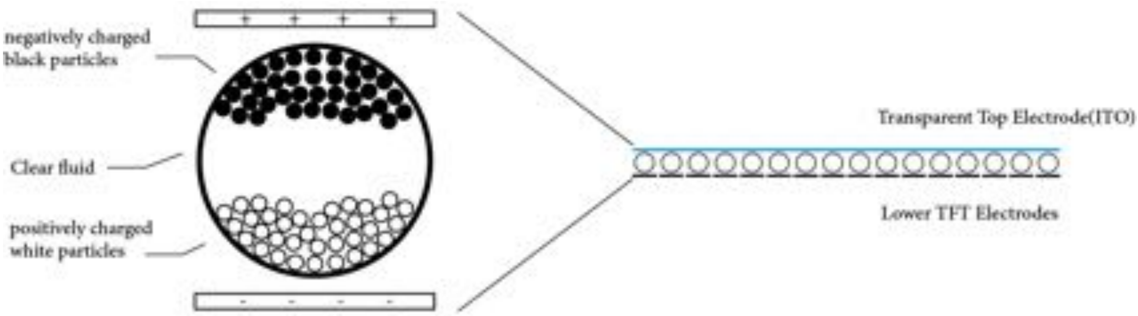


Figure 2.1: Schematic of eletronic paper. A layer of capsules is sandwiched between two electrodes, a transparent top electrode and individually controllable bottom electrodes. Each capsule is filled with contrary charged black and white particles. Depending on the lower electrode, the viewer sees from above only the black or the white particles.

Electronic Paper was first introduced in 1970 by Nick Sheridon and put into brought commercial use by Joseph Jacobsen from the MIT Media Lab in 1997 by co-founding the

E-Ink Corporation. E-paper is based on electrophoretic movement of colored particles in a fluid. Figure 2.1 shows the principle construction of a display. The screen layer consists of capsules with a thickness of $20 - 100\mu m$ each[Wong u. Salleo 2009]. A capsule is filled with thousands of charged nano-particles, which are suspended in a fluid. For monochromatic displays, there are black and white particles, which are charged positively and negatively, respectively. These particles are suspended in a separating fluid. The capsule itself is sandwiched between two electrodes. Depending on the polarization of the electrodes, the charged particles are attracted to the contrary charged electrode. While looking from above, one either sees the white particles, which makes the pixel appear white or vice versa. The displays are thereby not actively emitting light, but reflect the ambient light of the environment. This resembles the natural look of traditional paper. This technology offers high resolution displays with fast switching times and a very low energy consumption, because the particles stay at their location without an electrical field. Even though rigid, monochromatic displays are currently the most wide spread type, flexible RGB displays based on electronic paper had been shown as prototypes but are not commercially available so far. As to the knowledge of the author, there are no electrophoretic inks available for ink-jet or screen printing in a simple lab environment.

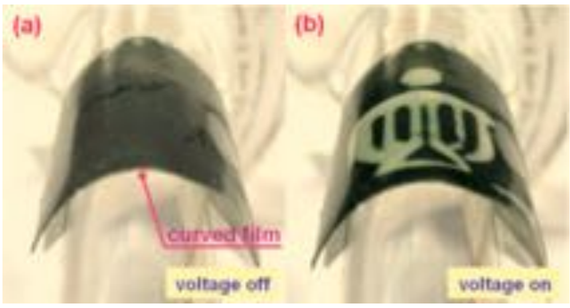


Figure 2.2: Thermochromic display on a flexible, conductive PEDOT:PSS substrate. **Source:** [Liu u. a. 2007]

Thermochromic displays[Liu u. a. 2007] consist of a thermosensitive material, which changes its color according to its temperature. A heating element, usually an electrode with a sufficiently low resistance, is placed under a layer of thermochromic material. When a current is applied to the electrode, the generated heat increases the temperature of the thermochromic layer. The heated parts then change their color or evolve from transparent to opaque. These kinds of displays are less complicated to fabricate. However, they suffer from low switching times since the heated parts need a specific time to change their temperature. Additionally, the evolution of heat follows the physical heat equation

$$\frac{\delta u}{\delta t} = div(\nabla u) \tag{2.1}$$

Since the color of the display behaves according to its heat, the temperature can be seen as color intensities. As pointed out by [Weickert. 1998] such a heat equation behaves exactly as homogeneous gaussian blur. It is therefore expectable that the edges of displayed shapes are unsharp. Figure 2.2 shows a thermochromic displays. The shapes indeed show blur at the edges and even more in the corners.

Electrochromic displays[Andersson u. a. 2007] behave in a very similar way to their thermochromic counterparts. Instead by heat they are excited by an electric current. This enables sharp edges at the borderlines of display segments[Ersman u. a. 2013]. They are also easy to fabricate but suffer from shortcomings like slow update times. Both display types do not actively emit light.

Organic Light-Emitting Diodes(OLED) are up to now widely used in consumer electronics to provide high-contrast displays, which offer high resolutions and a large range of reproducible colors. They are based on solid state luminescent layers of organic compound, which are sandwiched between two electrodes. Altogether, at least six layers are necessary to be applied on a film to construct an OLED display[Kitai 2008]. Up to now, the coating can only be applied efficiently by vacuum-thermal evaporation and the resulting layer needs to be properly sealed against oxygen and water. These procedures require a high-end print lab environment, which makes it impossible to produce on low-budget. Recently, bendable and fully rollable OLED displays had been shown as prototypes but are not commercially available up to now.

Thin film electroluminescent(EL) displays are a simple form of OLED displays. They consist of at least four layers[Kitai 2008]; a phosphor layer, which is sandwiched between two electrodes and an additional dielectric layer, which protects the electrodes against an electric breakdown. The layers are ultra-thin such that a display is only $10 - 180 \mu m$ thick. Since the emission of light happens due to the excitation of electrons in a solid state process, the displays are extremely durable up to 50.000 hours and provide very fast switching times. Additionally, such displays can be printed on flexible material, which makes them bendable and even foldable. The phosphor itself consists of small polycrystalline bulk particles, which form a homogeneous, luminous surface when printed. Their maximal brightness ranges between $100 cd/m^2$, which is equivalent to a bright LED, up to $1500 cd/m^2$[Kim u. a. 2011]. Nowadays, electroluminescent displays are often used for lighting and artistic purposes[Franzke 2013; Tech Last]. Due to their robustness against extreme temperatures between $-60°C - 105°C$ [Lumineq Last], EL displays are also well suited for medical or military purposes.

Inspired by [Franzke 2013; Telhan Last], we [Olberding u. a. 2014] propose the fabrication of custom-shaped EL displays. The four layers of these displays can be printed by a simple screen printing method. Recent advances in chemical fabrication of screen printable inks allow for an easy processing and low curing temperature below $130°C$. The power supply relies on high voltage AC but very low current, which makes the technology save to use. Previous work constructed EL displays by cutting out segments from off-the-shelf EL panels and rearranging them to a display[Amiraslanov u. a. 2014]. In contrast to this, our approach uses high resolution printing solutions and thus, offers a tremendously larger design spectrum for such displays.

2.1.2 Applications of Flexible and Custom-shaped Displays

A large body of work underlines the need for flexible, interactive and custom-shaped displays in Human-Computer Interaction. In the following, we will focus on augmenting objects with displays. Later on, we also cover the need of visual feedback in the mobile and wearable context.

Xpaaand[Khalilbeigi u. a. 2011] presents a mobile interactive device, which features a rollable display. The form factors of such a display are dynamic and can be adapted to the current task. They used the change of size induced by the user as further input to enhance its interactivity. Since fully rollable displays were not commercially available in 2011, the prototype consists of two handles with a rollable paper in between. A projector from above the paper projects an image on the device. The device itself is tracked via a 6-camera OptiTrack system using the reflectance of IR markers. Further on, the handles are equipped with accelerometers to directly sense push and pull actions of the user. The authors show that such a device concept offers effective improvements in interaction with mobile devices.

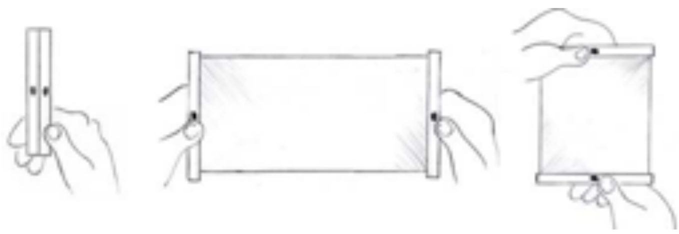


Figure 2.3: Xpaaand. A rollable display with two handles on the sides. The device can be adapted to different tasks by changing the width and the orientation of the display. **Source:** [Khalilbeigi u. a. 2011]

Pla and Maes of the MIT Media Lab investigated in 2013 the features of a cubic display [Pla u. Maes 2013]. Such a cube was constructed by augmenting each side of a cube with an OLED display. The authors show novel interaction technique that benefit from the free hand usage and the three dimensional form factor. Nevertheless, they used rigid displays with considerable thickness, which limits the design dimensions in space and deformation.

[Qi u. Buechley 2010] integrate paper-based pop-up systems with printed electronics.

Pop-up art is well known from books for children to let three dimensional structures pop up from the two dimensional page of a book. Including printed electronics in such structures enriches them with interactivity and visual feedback. The later was realized by gluing single LEDs on the paper. This limits the visualization space to point light sources and primitive shapes.

[Yeh u. a. 2006] declare that large paper prints offer a high spatial resolution but a small temporal resolution, while digital displays, on the other hand, offer a high temporal but low spatial resolution. Yeh et al. therefore propose to use both concept as an ensemble by enriching such traditional printouts with interactive displays and digital information. They show the integration of paper with projected displays and digital pens, which can track their position on the paper. Moreover they offer a framework to easily generate HCI applications with these modalities. Later work by [Song u. a. 2009] combined pen and paper interaction with visual feedback from a projector displayed on the paper plane and pen interaction *above* the surface. The pen is equipped with sensors that allow a remote computer station to track the movement of the pen in free air. The projector displays navigation menus and alternative layers on the paper surface, which can be controlled and modified by the pen, while menus and layer change with position and the distance of the pen to the paper.

In electronic engineering, it is common to realize a circuit design by constructing printed circuit boards(PCB). Their manufacturing generally involves two steps:

- milling the routed wires from a copper coated epoxyd plate
- soldering of electronic components like resistors or LEDs on the board

Concerning the first step, [Kawahara u. a. 2013] introduced a rapid fabrication method to ink-jet print such a wiring on flexible substrates like paper or PET foil. Unfortunately, it is hard to solder electronic components on temperature sensitive materials like paper. [Hodges u. a. 2014] introduced *Circuit Stickers*, which offer the possibility to simply glue sticker-like foil, which contains an electronic component on any printed circuitry. Such printed circuit stickers could be further extended with printable flexible displays, which are integrated in a printed circuit design.

Another research stream investigates interaction modalities of flexible thin-film diplays. [Lahey u. a. 2011] elaborated 24 bend gestures of a flexible e-paper display. By conducting a user study, they found out that three bend gesture pairs were interpreted by the participants as most intuitive. These are bending of the upper corner, the lower corner and bending of the whole display up and down. In a similar fashion, researchers from Carleton University proposed a new interaction modality by stacking flexible, thin-film displays on top of each other[Girouard u. a. 2012]. As Lahey et al., they used flexible e-paper sheets in their prototype. Additionally, they augmented them with a conductive point pattern sensor, which allowed them to sense touch and the relative position of one sheet to the other. They used bending of the sheet edges as well as touch input to organize the digital content of the stack. E-paper displays of course suffer from several shortcomings. Currently, only monochromatic displays are available and they have to deal with slow update times. Moreover, they needed an additional sensing layer for their prototype.

In the field of wearable and mobile computing, [Lyons u. a. 2012] developed an interactive wrist band. It is constructed entirely of rigid and square display segments, which loop around the arm. Their multi-touch sensitive surface allows for many interaction possibilities. Nevertheless, the prototype leaves a clumpy impression, since the displays do not adapt the natural form of the wrist, because the used displays are rather thick and completely rigid.

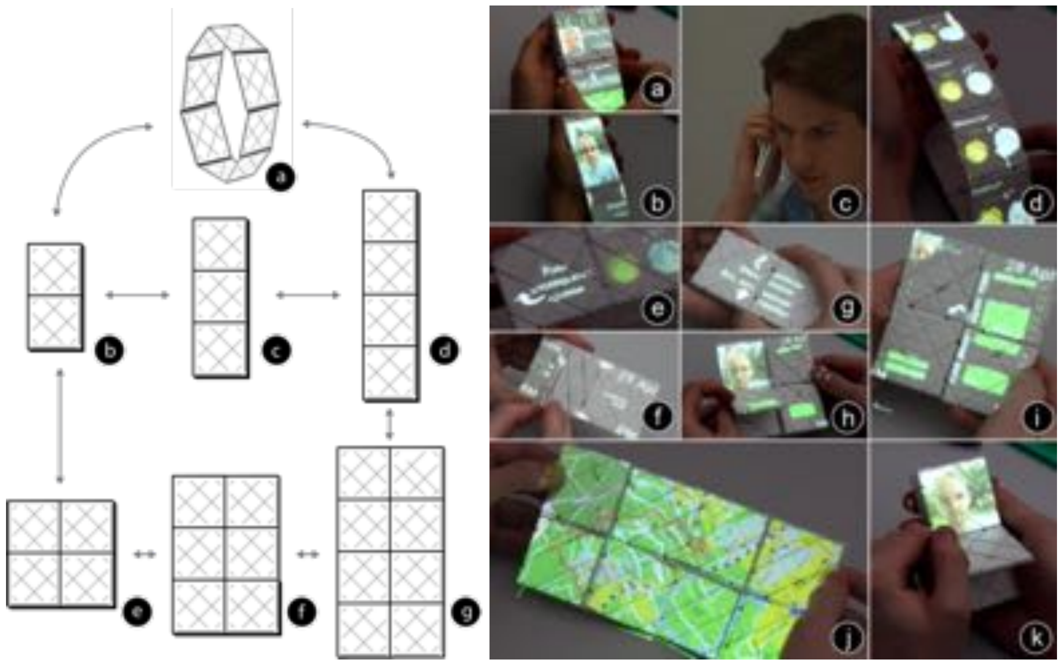


Figure 2.4: Puddle. **Left:** Overview of a subset of possible shapes of Puddle. Their constructing is based on the Rubik's magic puzzle. **Right:** Set of possible application cases for the device. **Source:** [Ramakers u. a. 2014]

Another step in the area of mobile computing was presented by [Ramakers u. a. 2014]. Their device consists of many rigid display tiles, which are connected between each other in a Rubik's magic 3D puzzle style(cp. figure 2.4). This versatile construction offers many different possible shapes. Each shape thereby acts as a distinguished visualization and interaction modus. Since up to now no displays are commercially available, which fit these form factors, Ramakers et al. used white PET tiles, which are illuminated by a projector above the device.

While the presented works on mobile computing so far based on rigid segments, [Steimle u. a. 2013] investigated interaction concepts for flexible displays. By using a HD projector and a kinect camera, they are able to display any image on a flexible substrate such as paper or foam with respect to various deformation that can be applied to a sheet. One key contribution of their work, is the markerless capturing of the display surface by using the depth information of the kinect camera and embedding them in a fast and robust optimization scheme. Second, they are able to remove occlusions by human hands, which appear when the displays is hold. Moreover, the system can project any image correctly deformed on the display surface.

Another stream of research investigates shape-changing devices. Recent work by [Roudaut u. a. 2013] introduces the term "shape-resolution" and gives a ten-dimensional feature vector to classify the changeability in shape of such devices. They evaluate their concept with *Morphees*. Morphees are mobile device that are able to change their shape by using Shape Memory Alloys(SMA). They can be augmented by flexible displays, which was up to 2013 only reasonable with e-paper or by rendering via a projector on a surface.

All mentioned work so far instantiates displays, with e-paper, single LEDs or projection-augmented paper-prints. As shown by [Olberding u. a. 2014], printing electroluminescent displays in any shape, a large variety of substrates and at high resolutions opens up considerably more degrees of freedom .

3 Physical Background

The main part of this thesis investigates displays, which are based on electroluminescence. Major properties of such devices can only be understood by studying the physical foundations and working principles of luminescent materials. This will provide insights to the representable color space, fabrication methods, lifetime and luminance properties as well as their power consumption and efficiency. This chapter is based on the books *Solid State Luminescence* and *Luminescent Materials and Applications* by Adrian H. Kitai as well as the *Handbook of Electroluminescent Materials* by D. R. Vij, which provide a well written in-depth investigation to the physics and principles behind luminescent materials [Vij 2004; Kitai 1993; 2008].

3.1 Principles of Luminescence

The emission of photons by a luminescent material cannot be explained without a brief introduction into nuclear and quantum physics. We will therefore start with an overview in the mentioned areas before we finally describe the luminesce effect.

3.1.1 Introduction to quantum physics

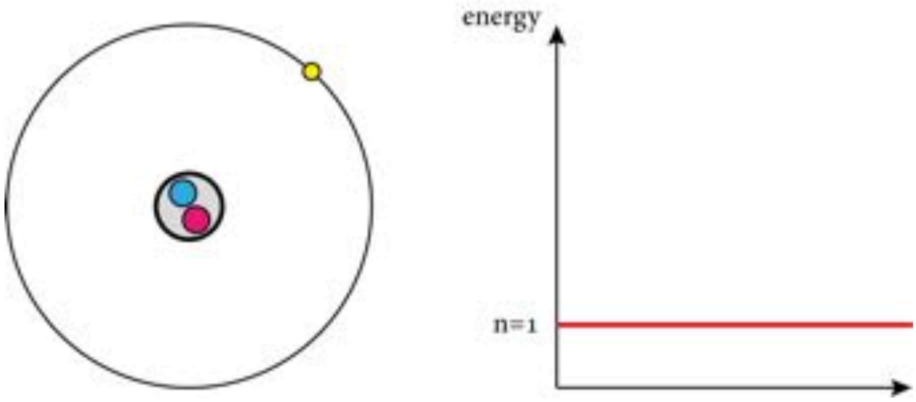


Figure 3.1: Deuterium Atom. The nucleus in the center consists of one neutron(blue) and one positively charged proton(red). A negatively charged electron(yellow) orbits around the nucleus. Since the electron is on the lowest orbit around the nucleus, its quantum state is $n = 1$.

The Bohr model of atoms describes an unexcited atom by a positively charged nucleus and one or more negatively charged electrons, which are on one or more orbits around the nucleus. The nucleus itself consists of neutrons and protons. For each proton one electron needs to be on an orbit around the nucleus to keep the atom electro-magnetically neutral. For a deuterium nucleus, which consist of one neutron and one proton, exactly one electron needs to be on an orbit(cp. figure 3.1).

Of course, it is possible that a nucleus contains more than one proton. The Lithium-6 atom, for example, consists of 3 protons and 3 neutrons. Thus, 3 electrons need to orbit around the nucleus to keep the atom neutral. As depicted in figure 3.2, two electron are on the lowest orbit, while the third is on a higher orbit. The central assumption in quantum physics enforces now that these electrons have discrete orbits, i.e. they are *quantized* and it is not possible for an electron to be in between two orbits. One can assign then each electron an integer n according to its orbit, where the lowest is $n = 1$. This integer is called *principle quantum number*. The energy of an electron depends on its quantum number n and can be described by

$$E = n * h * v \tag{3.1}$$

with h the Planck constant, v the frequency of the electron and $n \in N^+$. Application of Schrödingers wave equation to electrons around a nucleus led to the fact that the amount of electrons in each quantum state is limited. That means, there are at most two electrons allowed in the lowest orbit. Any additional electrons need to be on a higher orbit.

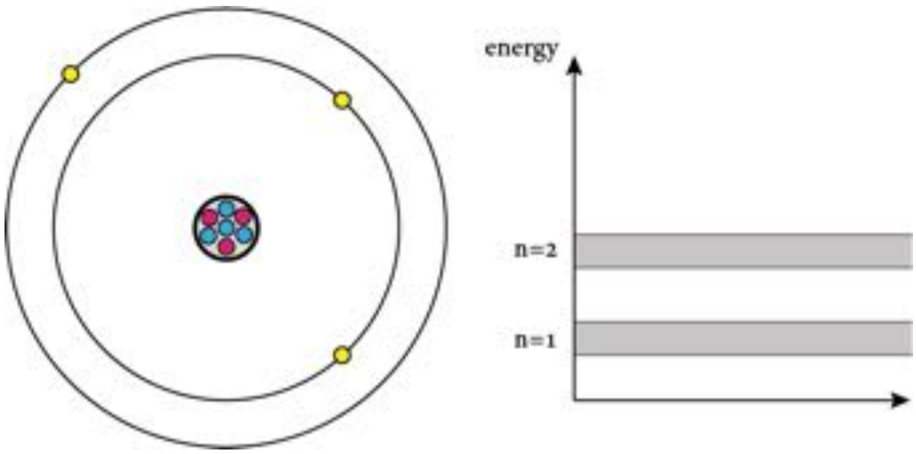


Figure 3.2: Lithium-6 Atom. The nucleus in the center consists of three neutrons(blue) and three positively charged protons(red). Three negatively charged electrons(yellow) orbit around the nucleus with two in quantum state $n = 1$ and one electron in state $n = 2$. Since we assume a large system of atoms with non-zero heat, the energy levels vary within a quantum band.

It is also possible that an electron jumps from a lower quantum state i to a higher state j by absorption of energy, for example, by a photon. The energy that is necessary for such a quantum transition can be described by

$$E = (j - i) * h * v \tag{3.2}$$

In this case, the atom is called *excited* since there are lower orbits, which are not full. Such an excited atom can fall down to an unexcited state again. In this case, energy is released according to formula (3.2).

The so far described model assumes a perfectly isolated atom with no kinetic energy, i.e. at 0 Kelvin. For real materials, one usually considers a large system of atoms or even a crystal lattice. For such systems, it is necessary to assume that electrons can be shared by different atoms and that vibrations(heat) of the neighborhood can influence an atom. In this sense, it is possible that the energy level corresponding to a principle quantum number can be slightly moved up or down. Since we consider a large system of atoms, we end up in a quantum band of many different but close energy levels for a quantum number n, a *quantum band*(cp. figure 3.2).

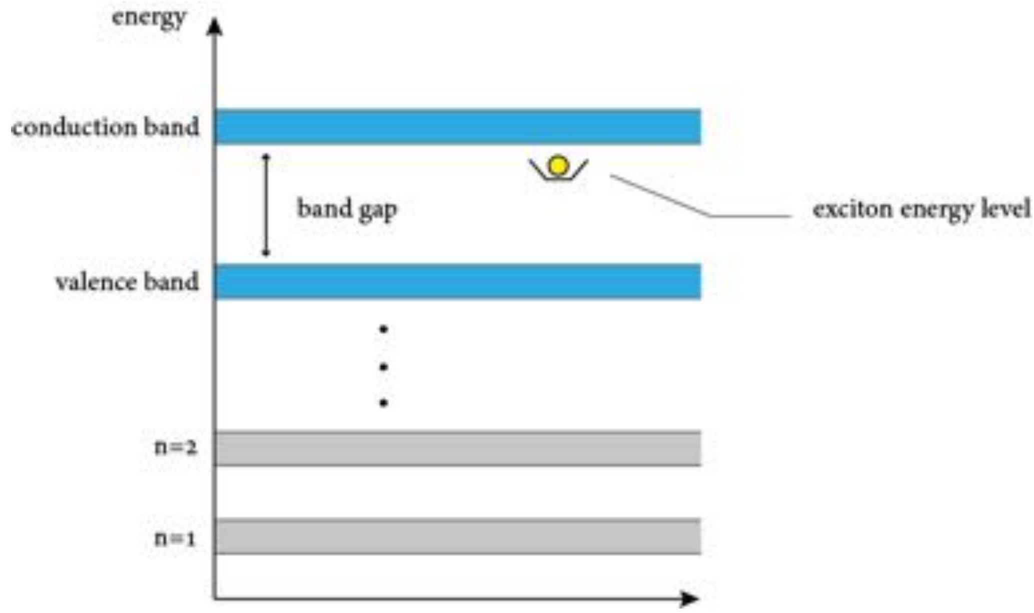


Figure 3.3: bandgap and excitons.

The upper most quantum number i, such that an electron has still a low enough energy level such that it cannot leave the attraction area around the nucleus, is called *valence band*(cp. figure 3.3). The lowest energy level, such that an electron can leave the orbits of a nucleus is called *conduction band*. The energy that is necessary for an electron to jump from the valence band to the conduction band is called *band gap*. If an electron leaves the valence band, an electron hole is left in the valence band, which can be seen as the absence of an electron. Since the atom contains at this situation more protons than electrons, the atom is called *(positively charged) ion*. Both the electron and the hole can move freely in a material lattice. Even if an electron had jumped from the valence band, its energy might still be a few meV to less to leave the atom and is still bound by electrostatic *Coulombic attraction*. Such an electron-hole pair is called *exciton*(cp. figure 3.3). Even though this pair is bound to an atom, it can jump from one atom to another in a crystal lattice. Excitons usually exists only for a very short time if the material is significantly hotter than 0K, i.e. at room temperature, until it recombinates with the release of energy in terms of photons, phonons and/or lattice vibration.

3.1.2 The luminesce effect

To lift an electron from the valence band to the conduction band, a specific amount of energy needs to be fed into the atom. This process is called *excitation*. The level of energy needs to be high enough to exceed the band gap. If this amount is not reached, no reaction will take place. Figure 3.4 shows the increase of luminance by increasing the electric field around a luminescent material. Obviously, the emission of photons starts at some minimal energy level. Such an action can be achieved by interaction of an atom with a photon, a free electron or an electric field. The types of luminescence are then called *Photoluminescence*, *Cathodoluminescence* or *Electroluminescence*, accordingly. If an exciton

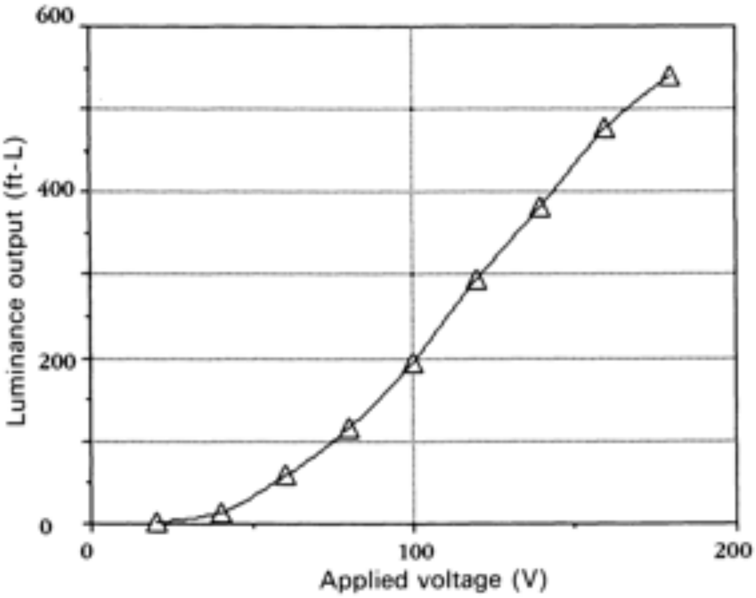


Figure 3.4: Typical voltage-brightness relation of an AC-driven electroluminescent lamp. Emission of photons needs to overcome a minimal voltage threshold. **Source:** [Kitai 1993]

recombinates(relaxes), the electron falls back into the valence band, releasing its energy as a photon. Its wavelength is thereby defined by the width of the band gap.

$$\lambda = \frac{c * h}{E} \tag{3.3}$$

with λ the wavelength, c the speed of light, h the Planck constant and E the energy that is released by falling down the band gap. Since the energy of an exciton is slightly below the band gap, the emitted photonic energy will be slightly less than the band gap. Also due to vibration(heat) of the atom and its environment, the energy level does not fall to its most probable ground state by recombination. The remaining energy difference to the ground state is then emitted as vibration to the lattice. Since this energy also is missing in the photon, one encounters a further decrease in wavelength. This effect is known as the *Stokes shift*.

3.2 Electroluminescent Phosphors and Colors

As we pointed out in 3.1.2, the luminesce effect is based on the recombination of excitons. Such excitons have the property to be able to move freely within a crystal lattice. A widely used luminescent material, for example, is a ZnS crystal. By introducing defects in such luminescent crystals, i.e. by doping with ions, it is possible to change the band gap of the crystal. Such an defect is called *luminescent center*. The excitons recombine in these centers with their different band gaps. This leads to a change in the wavelength of the emitted photons.

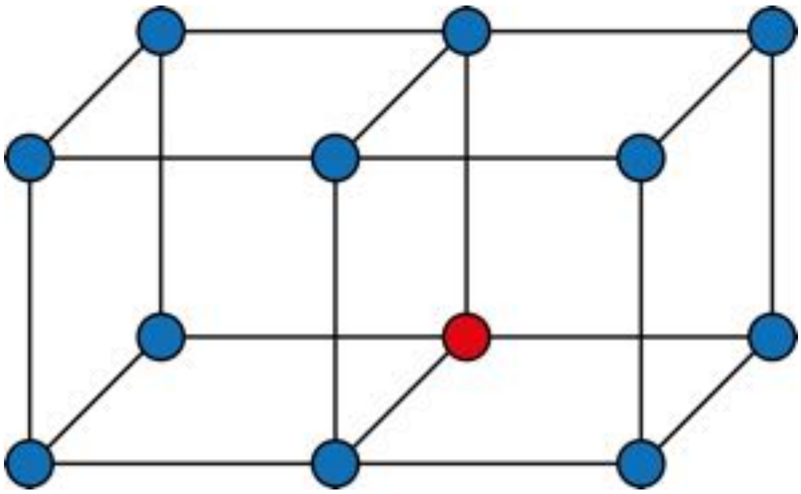


Figure 3.5: crystal lattice. A defect in the ZnS crystal structure was introduced by an copper atom(red). Excitons recombine in the copper with the specific band gap that has been evoked by the defect.

A prominent and well investigated example for such a crystal is ZnS:Cu. ZnS alone does not luminesce, but can be doped by Cu, which leads to deployment of blue light. In the electron-hole-combination model for luminescence as described above, the ZnS crystal acts as a donor, which provides electrons, which can then be in turn recombined in an acceptor, the luminescent center. Of course, it is also possible to dope the luminescent material with other donor elements. ZnS:Cu,Al contains a copper atom as the luminescent center and an aluminium atom as a donor. Since the amount of energy that is necessary for an electron to leave the valence band of the Al nucleus, is different to those of the ZnS crystal itself, the band gap between the Al nucleus and the Cu nucleus is different, leading to a different wavelength of the emitted photon. Furtheron, it is possible to dope a luminescent material with several luminescent centers, which then in turn emit photons of different wavelength corresponding to the amount of recombination with the one or the other EL center. Figure 3.6 shows a list of different EL materials. Figure 3.7 shows the wavelength of doped ZnS crystals with several luminescent centers and donor elements.

Phosphor	Color	CIE coordinates	Efficiency, l/W
1) $ZnS:Mn$	yellow	0.5, 0.5	3–10
2) $ZnS:Tb$	green	0.32, 0.6	0.5–2
3) $SrS:Ce$	blue-green	0.19, 0.38	0.5–1.5
4) $SrS:Ce, Eu$	white	0.41, 0.39	0.4
5) $BaAl_2S_4:Eu$	blue	0.135, 0.1	0.5–1.5
6) $SrGa_2S_4:Eu$	green	0.226, 0.701	1–2
7) $Zn_2SiO_4:Mn$	green	0.2, 0.7	0.5–2
8) $Zn_2Si_xGe_{1-x}O_4:Mn$	green	0.2, 0.7	1–3
9) $ZnGa_2O_4:Mn$	green	0.08, 0.68	1–2
10) $Ga_2O_3:Eu$	red	0.64, 0.36	0.5–1
11) $Y_2O_3:Mn$	yellow	0.51, 0.44	10
12) $Y_xGa_yO_3:Mn$	yellow	0.54, 0.46	10
13) $Y_xGe_yO_3:Mn$	yellow	0.43, 0.44	10

Figure 3.6: List of several phosphor types with their colors, CIE coordinates and the luminous efficiency. Note that the efficiency is reported in ranges. This is to account for different EL device structures. **Source:** [Kitai 2008]

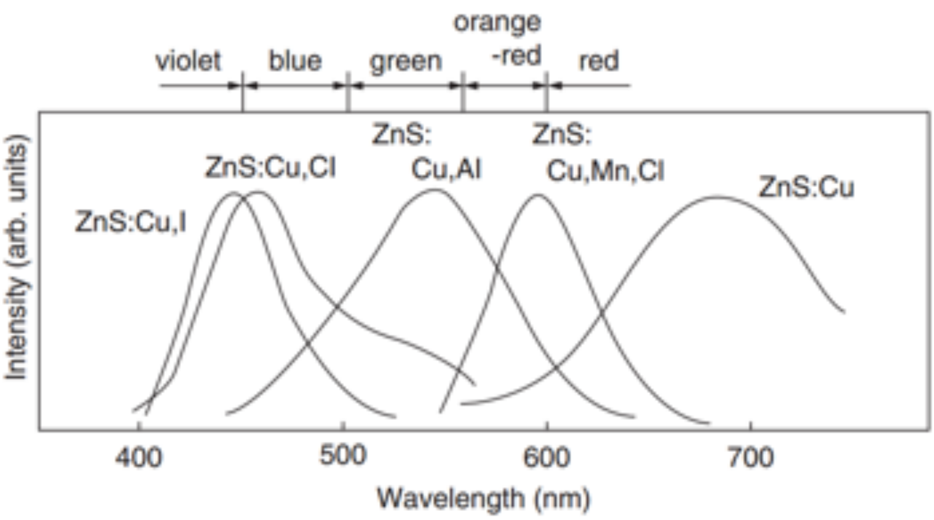


Figure 3.7: Spectra of ZnS crystals doped with several luminescent centers and donors in AC electroluminescent devices. **Source:** [Kitai 2008]

3.3 Powder Electroluminescence

In general, there are two ways of creating an EL panel. One is letting phosphor crystalize on a surface. Such displays are then called *Thin Film Electroluminescence (TFEL)*. The other is the use of EL powder. TFEL films can thereby last longer and have better brightness but they are less flexible than EL powder displays. Also, they cannot be printed directly, but must be chemically grown by a laborious process. EL powder on the other hand shows a slightly lower brightness and lifetime, but is therefore flexible, bendable, foldable and printable by screen printing. We will focus on EL Powder, because of the printing possibilities in a simple lab environment and the flexible structure of the resulting displays.

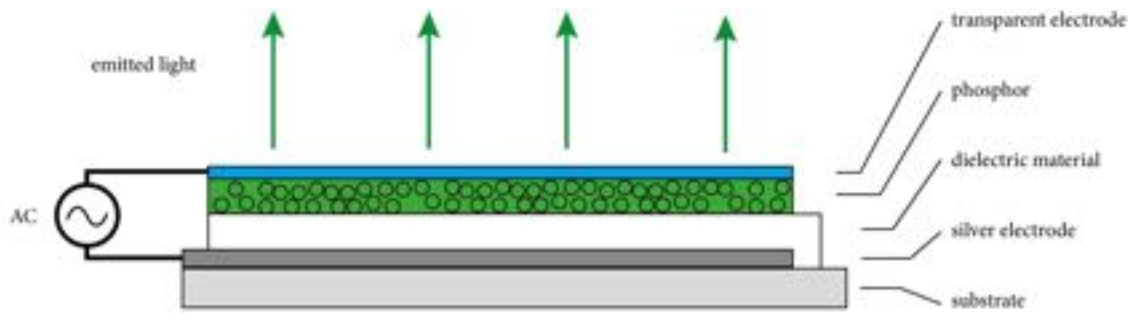


Figure 3.8: Schematic of an electroluminescent display. A luminescent phosphor layer is sandwiched between two electrodes. A dielectric layer protects the display against an electric break-down. If a high AC voltage is applied to the phosphor, photons are emitted through the transparent electrode.

The general structure of an AC powder EL device is shown in figure 3.8. The luminescent crystals are cut, for example by milling, down to bulk material of size $2-25\mu m$. The particles are then suspended in a dielectric, which is printed in a layer $50-100\mu m$ thick. This layer is then sandwiched between two electrodes, which are further isolated from each other by an additional dielectric layer to reduce the risk of an electrical break-down. Since only small, independent particles are used for EL, the resulting layer is bendable and foldable. Additionally, the particles in their suspension can be printed as long the printer nozzle is large enough to let the EL bulks pass. Since the particles usually are in varying size and even form groups of bulks(cp. figure 3.9), the minimal nozzle diameter needs to be significantly larger than the theoretical $25\mu m$. As to the knowledge of the author, there is no inkjet printing technique available so far due to the necessarily small printer nozzles.

3.3.1 Limitations of PEL devices

Lifetime, brightness degradation as well as energetic efficiency are key features of EL displays. In the following, we will discuss physical and chemical properties of EL powder

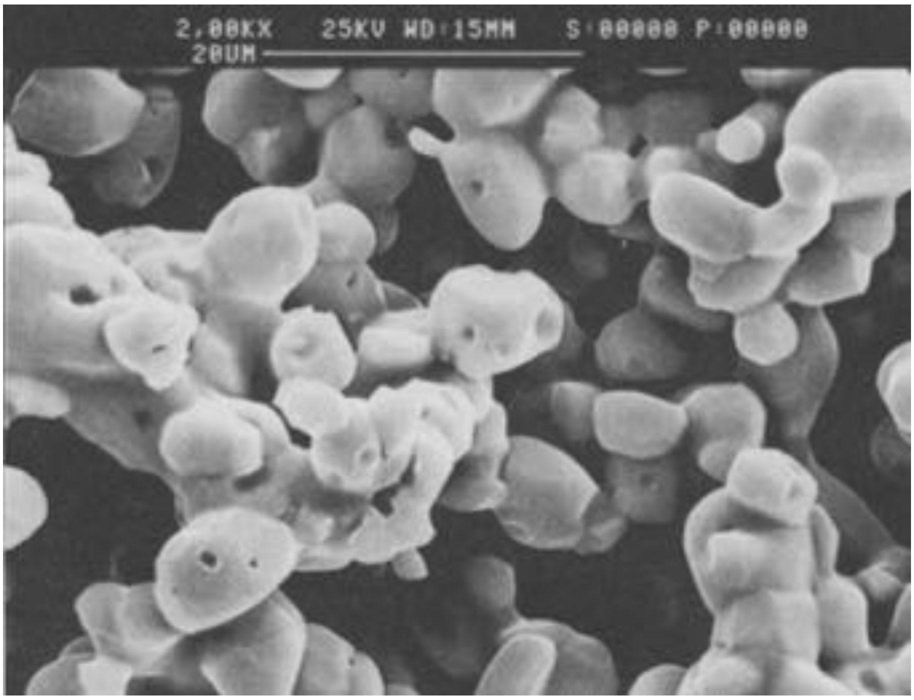


Figure 3.9: Phosphor powder for AC powered electroluminescent lamps. The phosphor particles show a tendency to bulk together and are not individually separated. **Source:** [Kitai 1993]

devices.

Lifetime and luminance degredation

The lifetime of a lamp is defined as the operating time until its brightness decreased to half of its initial value. Figure 3.10 shows a typical evolution of light emission over time of an powder EL device. The decrease of luminescence strongly depends on the applied AC frequency and the voltage. For a given voltage, the development subject to the frequency can be expressed by

$$\frac{L}{L_0} = (1 + \alpha t)^{-1} \tag{3.4}$$

where $\frac{L}{L_0}$ describes the relative brightness and α is proportional on the applied frequency

$$\alpha = \frac{4.5}{10^4 h} \tag{3.5}$$

The reason for such a behavior can be explained by the bipolar field-emission model presented by Fisher[Fischer 1971]. It states that during the production of luminescent ZnS phosphor at high temperatures around $1100 - 1200C^{\circ}$, highly conductive $Cu_{2-x}S$ needles are formed, which are a main reason for the high brightness of EL devices. When the lamps are activated and a high electric field is applied to the phosphor, the copper

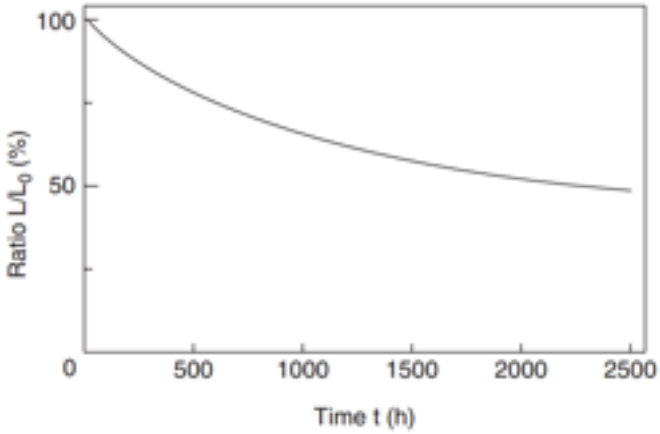


Figure 3.10: Relative degradation of brightness over time of a powder EL device. The luminance decreases asymptotically towards zero over time. The relative lifetime, which is the time until the lamp lost 50% of its brightness, is reached after 2500 hours. The lamp is powered by an inverter at 200V and 400Hz. **Source:** [Howard 1981]

atoms are attracted by the ZnS lattice and diffuse into them. Subsequently, the copper sulfide needles are destroyed, which lowers the overall brightness.

Moisture and environmental conditions

Another important obstacle of EL displays is due to the chemical property of ZnS, which are mostly used as a luminescent center carrier material. If the crystals are exposed to a humid environment, the ZnS reacts with water by

$$ZnS + 2H_2O \rightarrow SO_2 + Zn + 2H_2 \tag{3.6}$$

The sulfur and the zinc can escape from the crystal lattice, which is reported to diminish the observable brightness[Hirabayashi u. a. 1983].

To increase the lifetime of an EL display, it is strongly recommended to seal the lamp properly.

Power Supply and Consumption

Since the phosphor layer needs to be embedded in a strong electric field to reach useful brightness values, an AC voltage at $30V - 300V$ needs to be applied to the lamp at frequencies around $200Hz - 1.5kHz$. Increase of voltage or frequency leads to a more intensive brightness but also decreases the overall lifetime. Additionally, the most effi-

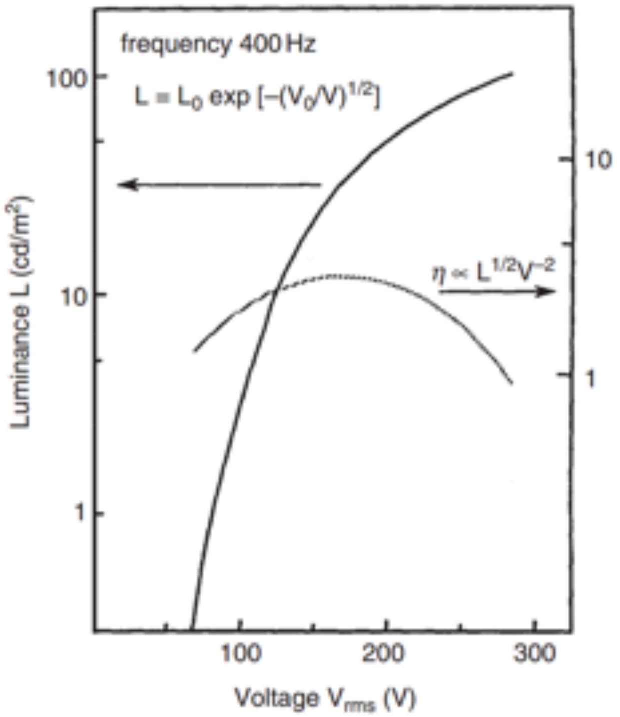


Figure 3.11: Typical relation between luminance and voltage as well as efficiency and voltage of an EL device driven at a frequency of 400Hz. **Source:** [Kitai 2008]

cient trade-off between energy consumption and luminance is reached below the maximal brightness at around $150VAC_{RMS}$ as shown in figure 3.11. The typical evolution of brightness corresponds to

$$L = L_0 \exp\left(-\left(\frac{V_0}{V}\right)^{\frac{1}{2}}\right) \tag{3.7}$$

The overall illumination efficiency is still high, compared to traditional light sources. Since the emission process of photons happen in a solid state without a large development of heat, a display consumes $2.6mW/cm^2$, while driven with $220VAC_{RMS}$ and $1.2kHz$. Nevertheless, the power efficiency depends on the thickness of display and the used phosphor type and might therefore be lower for different displays.

3.3.2 Applications of PEL devices

The particle-like structure of powder phosphor allow to fabricate very flexible and robust displays, which are bendable, even foldable and can cope with piercings and cuts. Their very thin structure down to $100\mu m$ further adds to their flexibility.

Due to improvements in the production of the luminescent materials, it is nowadays possible to reach a stable brightness at around $300cd/m^2$. This luminance output is still too small for an EL lamp to be used as room illumination, but offers many useful applications as a display, an interface of for design purposes.

Another feature of the particle-like structure of the luminescent material is the possibility to suspend them in inks. They can then deposited by printing technologies like screen printing on many flat materials, which opens up a wide range of possible printing substrates. Additionally, such displays can be fabricated without an expensive lab environment, which offers new perspective to practitioner and non-experts. AC powder EL devices are thereby the only flexible, ultra-thin light-emitting device that is available for reasonable costs on the consumer market.

4 Fabrication of Electroluminescent Displays

Besides the excellent properties of electroluminescent displays in terms of flexibility and energy consumption, the fabrication of this technology does not need to be done in a high-end lab environment with expensive machines and under the supervision of experts. In this chapter we will investigate the available printing technologies that allow non-experts to easily and inexpensively produce thin-film touch-sensitive displays. By first describing a general design space of these displays, we will start describe all necessary tools and materials to perform fabrication with screen printing. We will also discuss several construction types and discuss their properties. After this we will present the fabrication with ink-jet printing and show benefits and limitations of this technique. Followed by giving information about the power supply and the security instruction, we will finally present our approaches to connect printed electronics with a board controller or power supply.

4.1 Digital Design

When creating devices with off-the shelf displays, the designer has to choose between a limited selection of rigid rectangular form factors, which do not account for 3D shapes, curved displays or extreme aspect ratios. In contrast, fabricating customized electroluminescent displays offer a tremendously larger amount of freedom[Olberding u. a. 2014]. Figure 4.7 depicts two enabling design dimensions, i.e. *shapes* and *display primitives*.

Shapes
At first, the designer can choose between arbitrary 2D outlines of a displays. Their size can vary between small displays with less than $1cm^2$ up to large scale segments. Screen printing frames of sizes from A4 up to A2 are easily available on a hobbyist's level. While it is not possible to directly print on 3D objects with common screen printing and ink-jet printing devices, it is however possible to print on flexible substrates. These substrates can be bend and folded later on to create 3D surfaces. In the same way the displays can even be made shape-adaptable by bending, folding or rolling.

Display Primitives
Secondly, the designer can choose between a variety of display primitives. While one would intuitively expect a matrix-like architecture, it can be a compelling option to print single- or multi-segmented displays if the content is known at design time. Homoge-

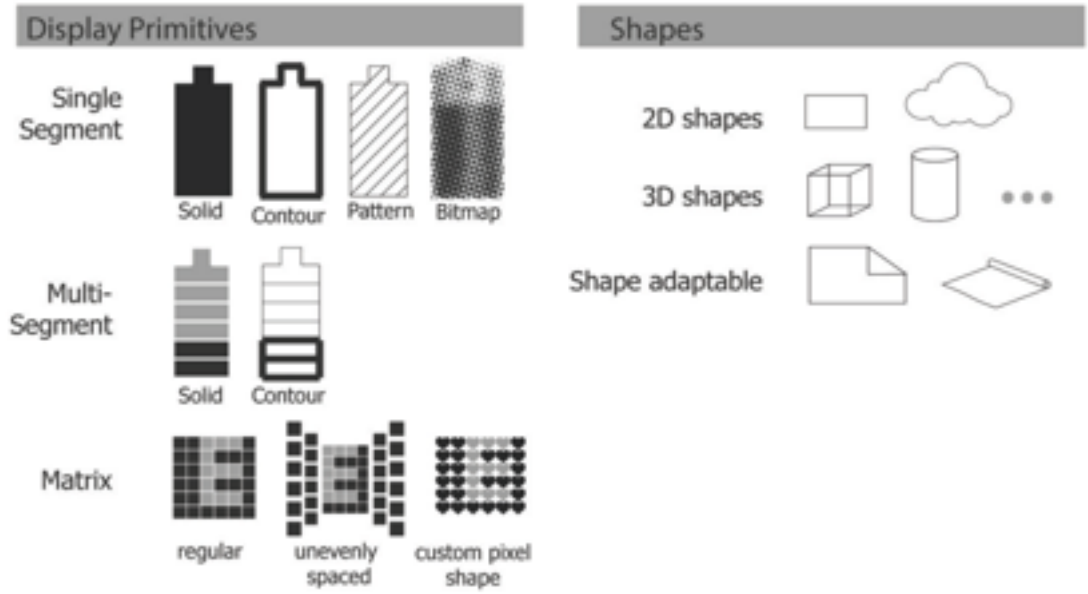


Figure 4.1: Design dimensions of customized electroluminescent displays. The designer can choose between various shapes and displays primitives. **Source:** [Olberding u. a. 2014]

neous segments can be printed in arbitrary shapes and with sharp outlines, while being easy to control. Print resolutions up to 60ppi for screen printing and 75ppi for ink-jet printing are possible. Moreover, there is no restriction to only print homogeneous segments. The areas can be filled with line patterns such as contours. It is also possible to simulate gray scales within a segment by *halftoning*. This is a technique known from print media and makes use of printing single dots of ink with different radii and distances between each other to make a region appear brighter or darker. Such a non-solid fill is easily created by altering the phosphor layer, while the upper and lower electrode are printed as for a solid segment. If dynamic content is necessary, also matrix architectures are realizable. Besides the standard construction of a regular matrix, EL displays allow to produce unevenly spaced pixels, for example, to offer high resolutions in the center of a display and low resolutions at the unimportant border regions. The shape of each pixel can be altered likewise. This can create unique appearances of a display. All these modifications only need to be specified during the design phase and do not produce additional effort during fabrication.

4.2 Fabrication

In this section, we will investigate two fabrication methods that allow non-experts to produce electroluminescent displays. At first, we will present screen printing for high quality prints. This technique is mostly known for printing colored ink on textiles but is recently often used for printing electronics. Secondly, we will present ink-jet printing as an instant fabrication process.

4.2.1 Screen Printing

Screen printing is a stencil based printing method, which is used in industrial and graphical arts since the end of the 19th century. Nowadays, it is often associated for printing on textiles, but also has applications in large scale printing on paper and printed electronics. Its popularity is mostly related to its simplicity and the ability to print with various inks and on various substrates.

The possibility to produce electroluminescent displays with screen printing in a simple lab environment is due to recent advances in the ink production. We will therefore discuss in the following functional inks and their properties, which are necessary for the fabrication of EL displays. Additionally, we will discuss different constructions of electroluminescent displays, which account for the various requirements the user might have for the display, e.g. good bendability or maximal robustness. Finally, we will give an in-depth description of the screen printing process and the usage of functional inks.

Inks

As we have seen in previous chapters, there are essentially three types of layers involved in the display construction. This is a conductive layer, a dielectric layer and a phosphor layer. For each of these layers, there exist several inks with varying optical and chemical properties, which allow the fabrication of a variety of different displays types with various properties. While a complete classification of all existing inks of these types is beyond the scope of this thesis, we will focus in the following on a selection of easily available inks of the Gwent group[Gwent Last] that are optimized for producing electroluminescent displays. During the later experiments, we only used inks of this vendor.

Conductive Ink
This ink family is able to transport current and is used as the top and the bottom electrode of an electroluminescent lamp. A silver-based ink offers a high conductivity and

is easily printable with a large variety of net resolutions, but is opaque, which renders it useful only for the lower electrode of an EL display. Alternatively, a carbon-based clear conductor can be used as the top electrode. While it is transparent to some degree, its conductivity is considerably lower than silver-based inks. Additionally, the clear conductor of the Gwent Group shows a blueish appearance, which will also alter the initial color of an underlying light source. Other vendors already developed screen printable conductive inks, which are neutral in their color[Henkel Last]. Since we used only products of the Gwent Group, we show only a comparison of conductive inks, which were available by the Gwent Group (c.p. figure 4.1).

	sheet resistance	**screen type**	**curing conditions**
Silver Ink C2131014D3	$100m\Omega/cm^2$	156-325lpi $\approx 60-130$lpc	$130C^\circ$, 3 minutes, heat gun $130C^\circ$, 10 minutes, oven
Clear Conductor C2100629D1	$500-700\Omega/cm^2$	195-355lpi $\approx 80-140$lpc	$130C^\circ$, 5 minutes, heat gun $130C^\circ$, 15 minutes, oven

Table 4.1: Ink properties of conductive inks of the Gwent Group. **Source:** [Gwent Last]

Both conductive inks consists of spheric nanoparticles with a diameter between $1nm$ and $100nm$, which are distributed in a binder fluid. The silver ink consists of silver nanoparticles, while the clear conductor is carbon-based[Gwent Last]. When two or more particles get in contact with each other, they can merge together into a cluster due to their large surface curvature[Perelaer u. Schubert 2010]. This process is called sintering and enables the conductivity of the ink. Unfortunately, this reaction can happen even at room temperature within the binder medium. Therefore, the nanoparticles need to be protected from each other to keep them individually stable. This separation is realized by alkyl chains and organic binders to establish chemical stability and optimal printability of the ink[Lovinger 1979].

After printing a layer of such an ink, the binder liquid and the particle-separating chemicals need to be removed. This is done by a curing process, where the ink is heated up. By increasing the temperature, both the binder and the particle separation can evaporate. Since the particles can easily get in contact with each other now, the sintering process starts. A high temperature accelerates the clustering of the particles. Recent developments in the ink fabrication allow to lower the necessary curing temperature down to $130C^\circ$, which makes this ink printable even on heat sensitive materials like paper and PVC.

Dielectric Ink

This ink is used to isolate the bottom and the top electrode of a display from each other against an electrical breakdown. Of course, this material should not affect the electric field between those two electrodes since the available energy should only be absorbed by the phosphor layer to induce an emission of photons. The amount of resistance that is created by a material inside an electric field is called *permittivity*. A high permittivity is therefore necessary when fabricating electroluminescent displays.

Dielectric Materials offer such a high permittivity. It acts as an electrical insulator that can be polarized by an electrical field. In contrary to a conductor, there are no moving charges within a dielectric material. Nevertheless, the contained charges within the material can re-orientate according to an electrical field and letting it pass through with negligible interference.

For screen printing, one often uses a binder liquid that is filled with particles that have a high dielectric constant such as barium titanate powder. The binder determines the viscosity and the color of the ink. While the Gwent Group only has a limited selection of different colors (c.p. figure 4.2), the creation of arbitrary colors for the dielectric materials is an easy process by just mixing colored pigment into a dielectric ink.

	screen type	**curing conditions**
White Dielectric Ink	156-325lpi	$130C^{\circ}$, 3 minutes, heat gun
D2070209P6	$\approx 60 - 130$lpc	$130C^{\circ}$, 10 minutes, oven
Pink Dielectric Ink	156-325lpi	$130C^{\circ}$, 3 minutes, heat gun
D2090130P5	$\approx 60 - 130$lpc	$130C^{\circ}$, 10 minutes, oven

Table 4.2: Dielectric ink properties of the Gwent Group. **Source:** [Gwent Last]

To remove the solvent fraction of the dielectric ink, a curing step is applied after printing. As for the conductive silver ink, the layer is cured at $130C^{\circ}$ for 3 minutes under a heat gun or 10 minutes in an oven.

Phosphor Ink

The last ink type is the light emitting phosphor ink. As already discussed in previous chapters, it consists of big phosphor particles with $10 - 50\mu m$ diameter. The particles are distributed in a dielectric binder liquid, which does not interfere with the applied electrical field. There are several phosphor types, which can generate different colors(c.p. figure 4.3). A larger selection of such phosphors has been discussed in chapter 2. When having raw phosphor powder available, it is even possible to mix different types of phosphor together in a binder liquid to create unique mixtures of colors.

When working with phosphor inks, one has to account in the printing preparation for the large size of the particles. In contrary to inks with small particles, the phosphor bulks tend to sink to the ground rapidly, while the binder is moving to the top. This can happen within hours, which makes proper mixing compulsory before printing. Further on, mixing by moving a stirring staff in the phosphor ink can break down the particles, which

color	luminance	screen type	curing conditions
White C2101125P4	44.7 cd/m^2	at most 156lpi at most $\approx$ 60lpc	$130C^{\circ}$, 3 minutes, heat gun $130C^{\circ}$, 10 minutes, oven
Green C2070209P5	73.9 cd/m^2		
Orange C2070126P4	18.6 cd/m^2		
Blue C2061027P15	49.2 cd/m^2		
Blue/Green C2061027P13	76.9 cd/m^2		

Table 4.3: Phosphor ink properties of the Gwent Group. **Source:** [Gwent Last]

reduces the overall luminescence. It is therefore recommendable to horizontally roll the ink container for several hours or using a tumbler mixer every time before printing.

Finally, as for the other inks, the binder liquid is evaporated away by a $130C^{\circ}$ curing step. The curing times are the same as for the dielectric ink at 3 minutes under a heat gun and 10 minutes in an oven.

Display Structures

The general structure of an electroluminescent displays necessarily has to have a phosphor layer, which is sandwiched between two electrodes. To avoid a shortcut, the electrodes need to be insulated against each other by a dielectric layer. Since many inks and different types of conductive materials are available, there are also different ways to construct an electroluminescent display. In the following, we will present several ways of fabricating a display and discuss their properties.

Standard Build
The standard construction to print an electroluminescent display consists of a silver layer, an insulating layer, the phosphor layer and the clear conductor as the top electrode. This set-up shows a good printability even on difficult surfaces, which might be porous or rough. The lowest silver layer can be printed with both high and low net resolutions, which makes it capable of covering an irregular surface.

The top electrode is printed with the translucent clear conductor. This layer is only transparent to a limited degree and yields a loss in brightness for this lamp construction.

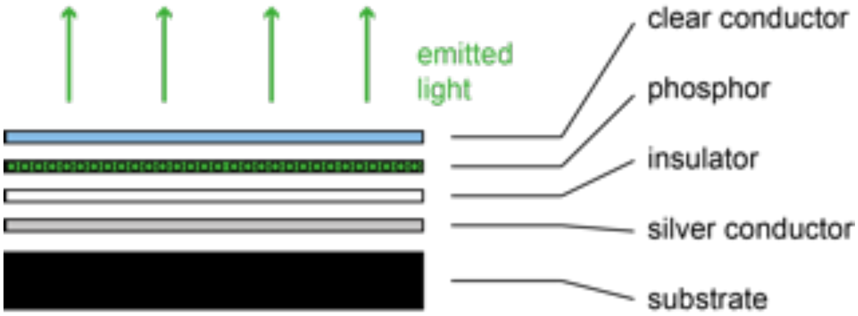


Figure 4.2: Standard Build. Schematic of the standard build of an electroluminescent lamp.

ITO Build

As we have seen, there is always one transparent electrode necessary in the construction to let the light escape from the electroluminescent phosphor. Beside the screen printable clear conductor, there are many alternatives in industry for transparent conductive materials. Probably the most prominent coating is ITO(Indium Tin Oxid). It is transparent with a visible light transmission rate of $\approx 90\%$ while still offering a good conductivity at $\approx 80\Omega/cm^2$ depending on quality and thickness of the ITO layer. Nowadays it is used in many application, where a high conductivity paired with a good transparency is required, like e.g. in the touch screen of mobile phones. The production of such coated sheets is laborious and most often done with a physical vapor deposition inside a vacuum. Even though it is therefore not possible to self produce such a material in a simple lab environment, it is easily available to order from many vendors like Gwent.

The main differences to the standard build of an electroluminescent lamp is that no substrate material is need. The ITO is already deposited on a flexible transparent PET sheet and all remaining layers are printed directly on the ITO. The produced lamp will be brighter than the lamp of the standard build due to the better light transmission rate of ITO and a better conductivity of the sheet compared to the clear conductor. Additionally, there is one layer less to be printed, which increases the fabrication speed. Nevertheless, the ITO coating can break easily if the flexible PET sheet is bend to much ($> 90°$). Also, the ITO electrode cannot be patterned easily and acts as one solid segment. This means that multiple segments or special shapes can only be realized in the phosphor or the silver layer.

Backlight Build

In many human-computer-interaction related applications, it is desirable that an interactive display is only visible, when it is used and vanishes, when it is not used. To enable such a behavior, it is possible to print displays on the back of translucent materials. Such

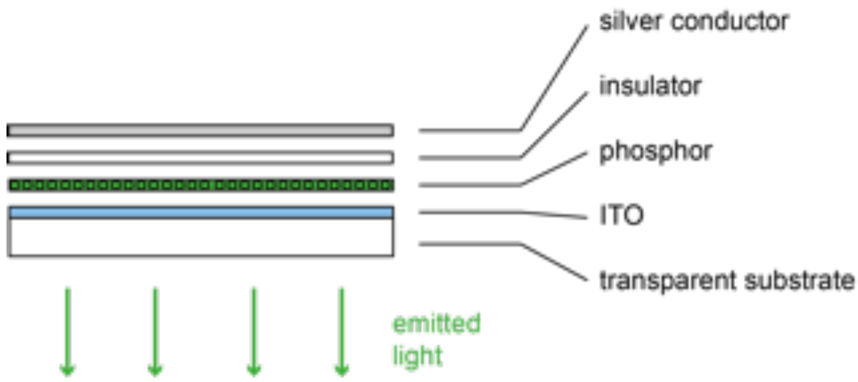


Figure 4.3: ITO Build. Schematic of the layers of an electroluminescent lamp, while using an ITO coated PET sheet as electrode.

semitransparent materials can be, for example, paper or even wood veneer. A display is printed on the back side of such a material with the light-emitting side directly on the substrate. When the display is turned on, the light shines through the material and let the display appear.

While this construction opens up many new applications and possibilities, one has to deal with a low overall luminance of the display, since the emitted light first has to pass through the material. Additionally, the material can cause sub-surface scattering, which leads to a blurring of the display contours.

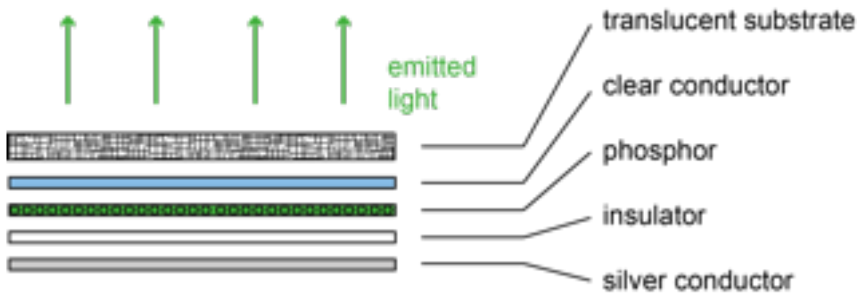


Figure 4.4: Backlight Build. Schematic of an electroluminescent display printed on the backside of a translucent substrate. The light emitting side of the display faces in direction of the substrate such that the display can shine through the material.

Translucent Build

Transparent and translucent displays have a wide range of application possibilities. They can be used in vehicles to show the driver information without distracting from the environment. Also, the displays can be seen from both sides enabling new interaction possibilities. To reach such display properties, it is necessary to get rid of all opaque layers, i.e. the dielectric layer and the silver conductor. The phosphor layer itself is already translucent and has a light transmission rate of 32% when using phosphor inks of the Gwent Group. While replacing the silver conductor in the ITO build with the clear conductor is a rather obvious choice, the replacement of the dielectric layer is not as trivial. A replacement for the insulating layer needs to be transparent on the one side but also offer a sufficient dielectric value.

Instead of printing such a translucent display on a transparent substrate, we propose to use the transparent base material directly as the insulator between the top and the bottom electrode. Experiments showed that many materials offer a sufficient dielectric value to let a phosphor layer emit light. Figure 4.5 shows such a display printed on ITO coated PET film. The film itself acts as the insulator and dielectric material. Note that the display is fully transparent, where no phosphor is printed.

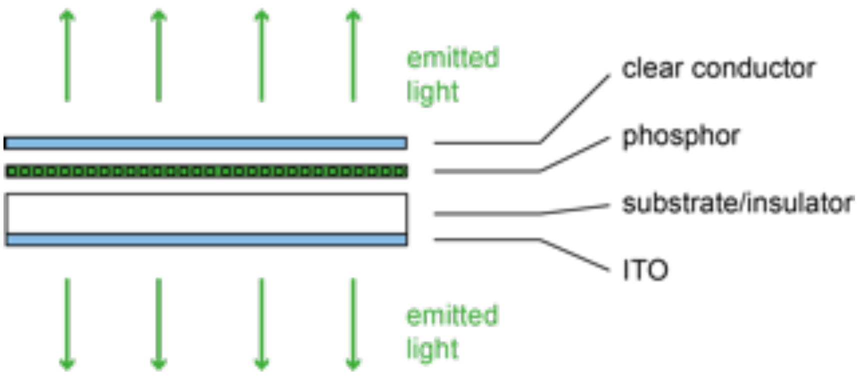


Figure 4.5: Translucent Build. Schematic of an electroluminescent display using the transparent substrate as the insulator and fully transparent ITO as electrode. The display shows a translucency of 32%, where phosphor is printed, while the display is fully transparent, where no phosphor is printed.

Materials

The selection of materials to print on heavily depends on its roughness. For screen printing in general, the print is easier and of higher quality, if the substrate surface is smooth. We conducted experiments by printing a filled circular shape with always the same screen printing net and the same display structure on various materials. Figure 4.6 shows the results. Materials with very smooth surfaces performed best and showed the largest brightness values for a given voltage. In contrast, rough materials like wood veneer were very difficult to print and show the lowest brightness intensities. This is because screen printing needs full contact of the net on the substrate. If a substrate surface topology is very rough, not all cells of the net can touch the substrate completely. These cells cannot unload their contained ink, which leads to holes in the print pattern.

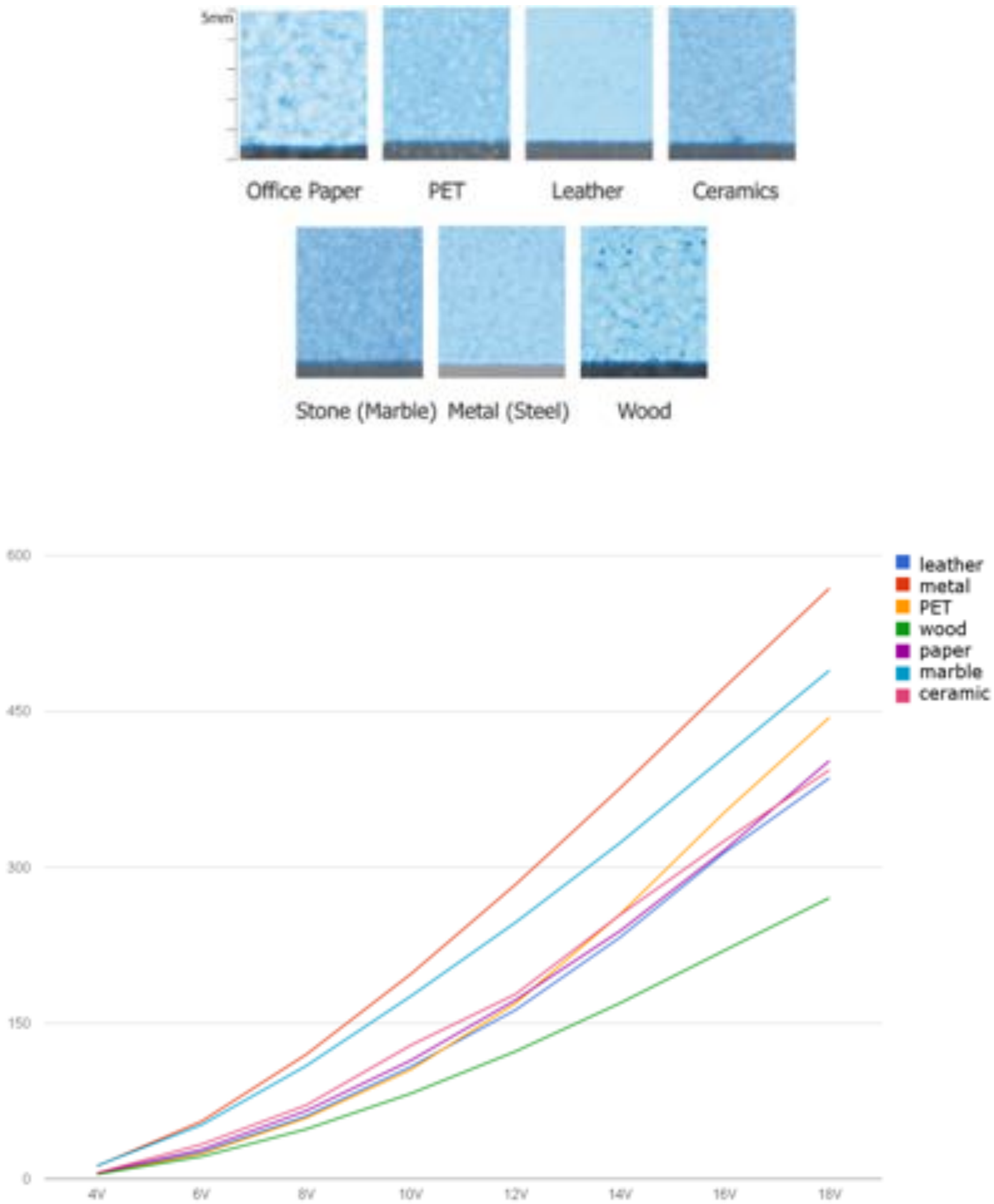


Figure 4.6: EL displays printed on different substrates. **Upper:** A $25mm^2$ section of activated displays on various substrates. **Lower:** The diagram shows the relation between DC Input on the display brightness. While flat materials like metal or marble show excellent brightness intensities, rough materials like wood reveal a lower brightness due to imperfections in the print.

Method

The general goal of screen printing is to transfer a predefined shape as a layer of ink on a substrate. The whole process can be divided into four consecutive stages, i.e. the digital design phase, the frame preparation, the printing phase and the recovery of the frame. In the following, we will describe these stages in more detail.

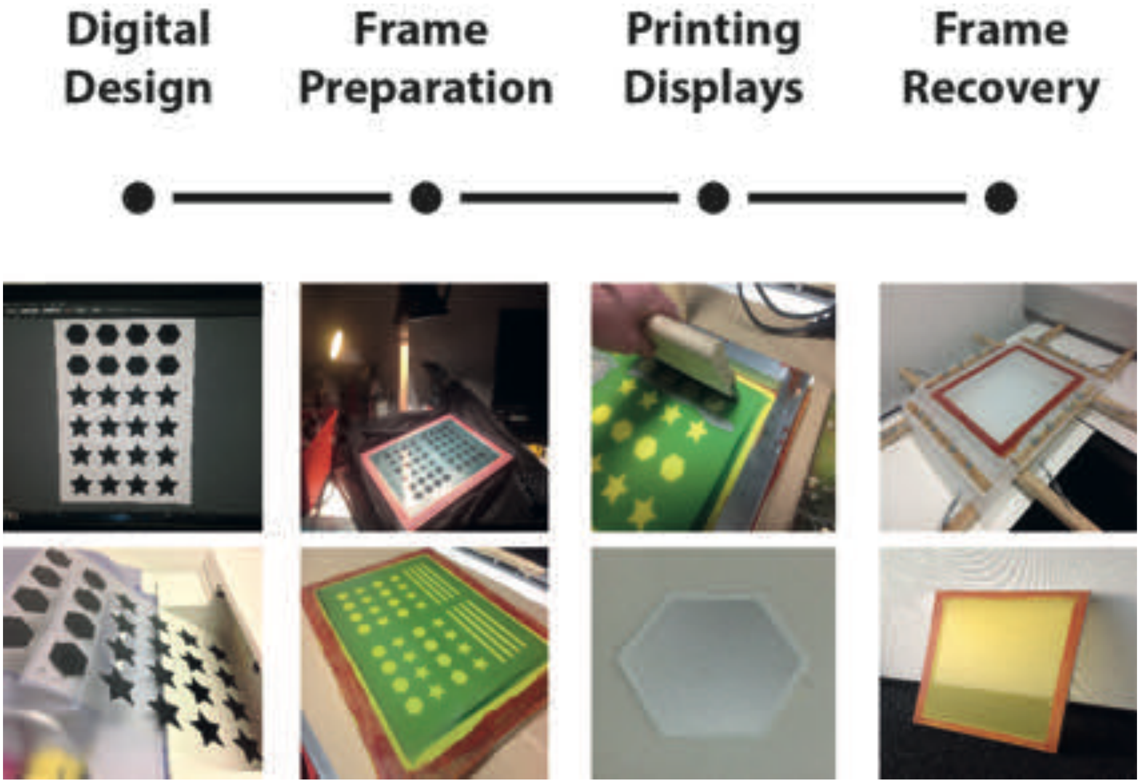


Figure 4.7: Fabrication Pipeline for electroluminescent displays using screen printing.

It all starts with a digital design. All layers, which should be printed later on, are created with a standard vector graphics program like Adobe Illustrator. The designer decides for the shape of the display and the display primitives(c.p. section 4.2). When this is done, all necessary layers for an electroluminescent display need to be created in the program. This depends of course on the display construction, which were discussed in the previous section. While the phosphor layer and the electrodes should have the same size, the dielectric layer should be chosen 1-2mm larger than the electrodes to ensure avoidance of a shortcut. Additionally, one often prints two layers of dielectric on top of each other to make sure that no holes in the insulator are left over due to imperfections in the print process.

After designing all necessary layers digitally, one can proceed to prepare the screen printing frame. The transfer of the designs to the screen printing net is realized by UV lithography. For that, the net is coated with a photosensitive emulsion. A UV light source irradiates the emulsion, while these shapes, which should later let ink pass, are protected. The irradiated areas become water-insoluble while the protected areas can still be removed with water. After washing, the net is only permeable at the designed shapes, while the rest of the net does not let any ink pass.

The prepared frame is placed above the substrate with a small distance of 1-2mm. Then a functional ink, applicated on the top side of the net, is pressed with a squeegee blade through the permeable areas of the net. Since all areas, which are covered by emulsion are impermeable, only the designed shapes will be printed on the substrate. The printed ink is then cured with a heat gun or an oven. The next layer can then be printed directly on top of the dried layer until the construction of a display is complete.

To ensure the highest quality in print, it is recommended to use each shape in the net only once for printing. One possibility, to reuse a net is to clean the shapes after printing. Oil-based inks like those that are used for electroluminescent displays, can be dissolved with thinner (e.g. aceton). Another way is to use a high pressure water cleaner and blowing the remaining ink out of the net. Both methods are very time consuming ($\approx 1 - 2h$) and implicate a high waste of thinner liquid or polluted water, respectively. We found out that the most easy way to recovery a frame, is to cut out the net completely and put a brand-new net into the screen printing frame. For that, the net is stringed on the frame and glued on it with a very strong two-component glue.

Frame Properties

After digital designing all necessary layers to fabricate a display, the next step in the production pipeline is to choose a suitable screen printing frame. There are mainly three important parameters to consider:

- frame material
- net resolution
- thread diameter

By varying these parameters, it is possible to control the printing resolution and the layer thickness of an EL display. Especially for difficult materials with rough surfaces, choosing the right combination of parameters decide about the success or failure of a printing attempt. In the following, we will discuss in detail these parameters.

Frame Material
A screen printing frame should offer the possibility to withstand large net tensions with-

out breaking or bending of the frame edges. These net tensions are necessary to keep the printing mask at its location during the ink application process when moving with the squeegee blade over the printer net. Additionally, the net jumps rapidly up from the substrate, which lowers the overall contact time between net and substrate. This further minimizes the risk of smearing. Desired properties for high-quality frames are therefore durability and stiffness.

The most popular materials for screen printing frames are wood, steel and aluminum. Due to increasing quality requirements, wood frames are nowadays mainly used for simple printing tasks. They are cheap and easy to get, which allows fast production cycles but they are easily deformable by a high string tension or even by changes in the humidity of the environment, which renders them useless for high resolution printing tasks. Steel frames offer a very large stiffness and open up the possibility for very high net tensions. They are often used in industrial machines and for demanding printing tasks. Nonetheless, their production is costly and they are prone to corrosion. That is why aluminum frames are nowadays dominating the hobby and industrial market. Even though they are more deformable than steel frames, they are very durable due to robustness against corrosion and still offer the possibility for large enough net tensions to produce high quality prints.

material	modulus of elasticity
steel	210,000 N/mm^2
aluminum	71,000N/mm^2
wood	12,000N/mm^2

Figure 4.8: Modulus of elasticity for different materials. **Source:** [Scheer 2007]

The deformability of a frame edge depends on the modulus of elasticity(MoE), which is a material constant. A large MoE implicates a low bending of a frame edge. Figure 4.8 shows the MoE constants for the discussed materials wood, steel and aluminum. Aluminum shows here reasonable stiffness compared to wood and steel. Together with its easy and cheap fabrication and long durability, it is the best choice for fabricating electroluminescent displays.

Net Resolution and Thread Diameter

A screen printing net is essentially a lattice-like fabric with uniformly distributed gaps in the net. Each gap, which is sealed by a coating does not allow ink to reach the substrate, while open gaps will let the ink pass to the substrate. The amount of gaps within an area determines the printable resolution of a screen printing frame. Similar to conventional inkjet printers, which determine their printing resolution in *dots per inch(dpi)*, screen printing nets define their resolution in *lines per inch(lpi)*. A line is in this case a thread and is counted per dimension. In most cases, the x and y resolution is uniform. As for inkjet printing, a high resolution allows to print very fine details.

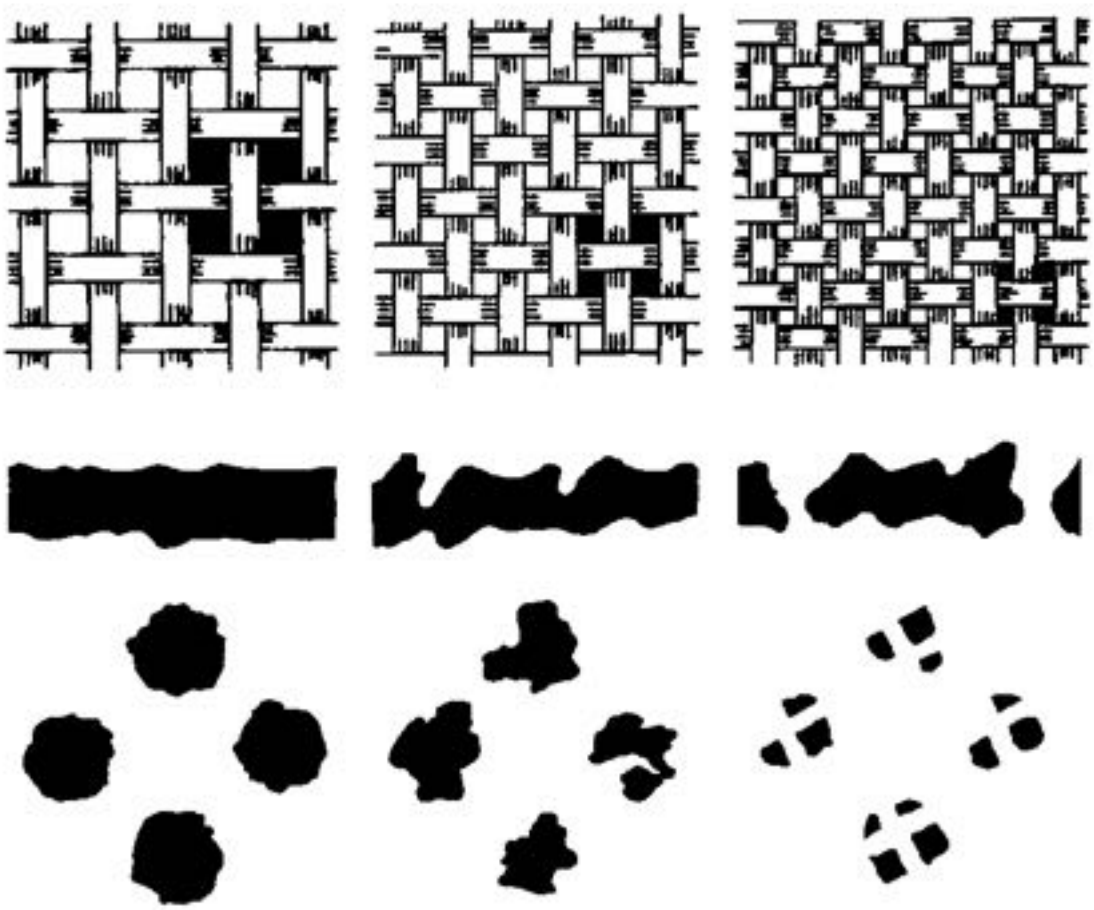


Figure 4.9: Varying mesh resolutions and the printing patterns, which result with increasing mesh resolution. **Source:** [Scheer 2007]

As depicted in figure 4.10, the amount of gaps increases with increasing lpi resolution, while the width of the gaps decreases. This has a direct implication for the print. Larger gaps will let more ink pass through the lattice, which yields a thicker layer of ink. Additionally, the ink of neighboring gaps will blend together on the substrate, which creates a continuous print layer. A high resolution net will let considerably less ink pass through. This can in turn lead to interruptions in the print pattern, if there is not enough ink available to blend together on the substrate.

The second parameter for meshes, besides net resolution, is the *thread diameter*. For commercial screen printing nets, it is often classified in four categories, namely S(=very small and light thread), M(=small and averagely light thread), T(=thick and heavy thread) or HD(=very thick and very heavy thread). These classifications, albeit very common, are not strictly defined and vary from supplier to supplier. The description is therefore often replaced by the exact thread diameter. Together with the net resolution, a net with 120lpi and a thread diameter of $31\mu m$ can be identified by the code *120 - 31*.

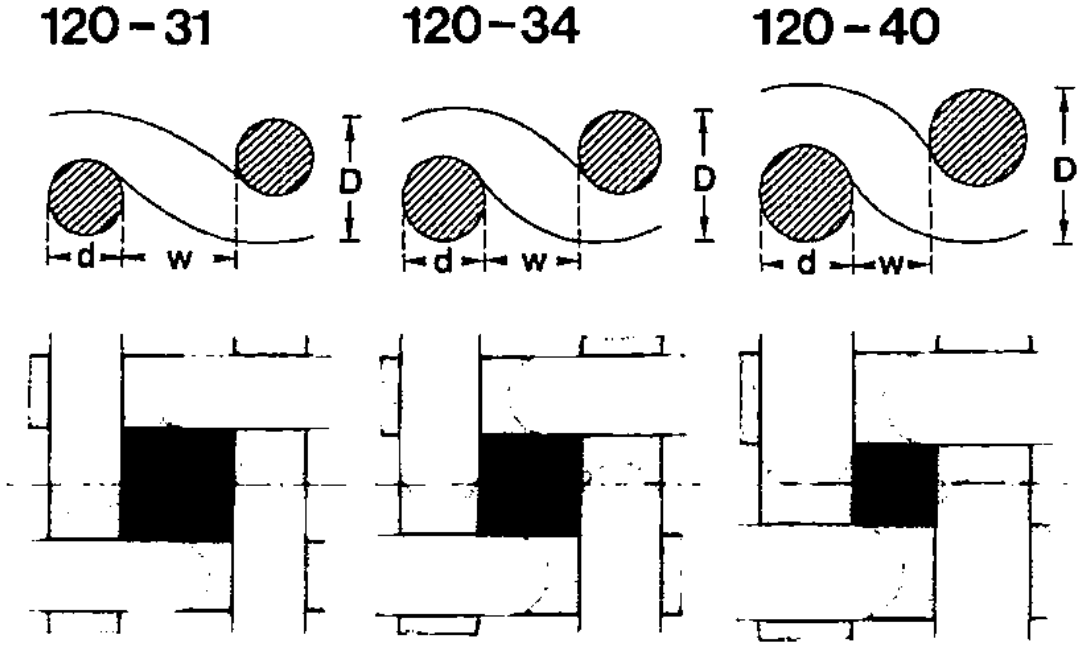


Figure 4.10: For a constant mesh resolution, the gap width decreases with increasing thread diameter. **Source:** [Scheer 2007]

A small thread diameter can provide larger gaps and the possibility to let more ink pass through a net. However, the elasticity of the net increases with the small threads, which shows disadvantageous properties in the net tension and the jump up speed of the net while printing. If the net does not jump up immediately after moving over the substrate with the squeegee blade, it is possible that the net smears the print image due to the squeegee blade movement.

Figure 4.11 visualizes the relations between varying net tensions, resolutions and thread diameters with respect to ink layer thickness and sharpness of the shape to print. The selection of an optimal relation between net resolution and thread diameter can be done in practice only by the experience of the screen printer, since many variables like the shape to be printed, the substrate surface and liquid absorptivity, the viscosity and particle size of the ink as well as the room temperature and the humidity play a role in the selection.

Frame Selection for Electroluminescent Displays

For printing electroluminescent displays, it is necessary to account for the different types of inks, which are used during the production, as well as the topology and the absorptivity of the substrate to be printed on. The inks vary in their viscosity and their particle size. All these parameters have an impact on the choice of the net resolution. While a

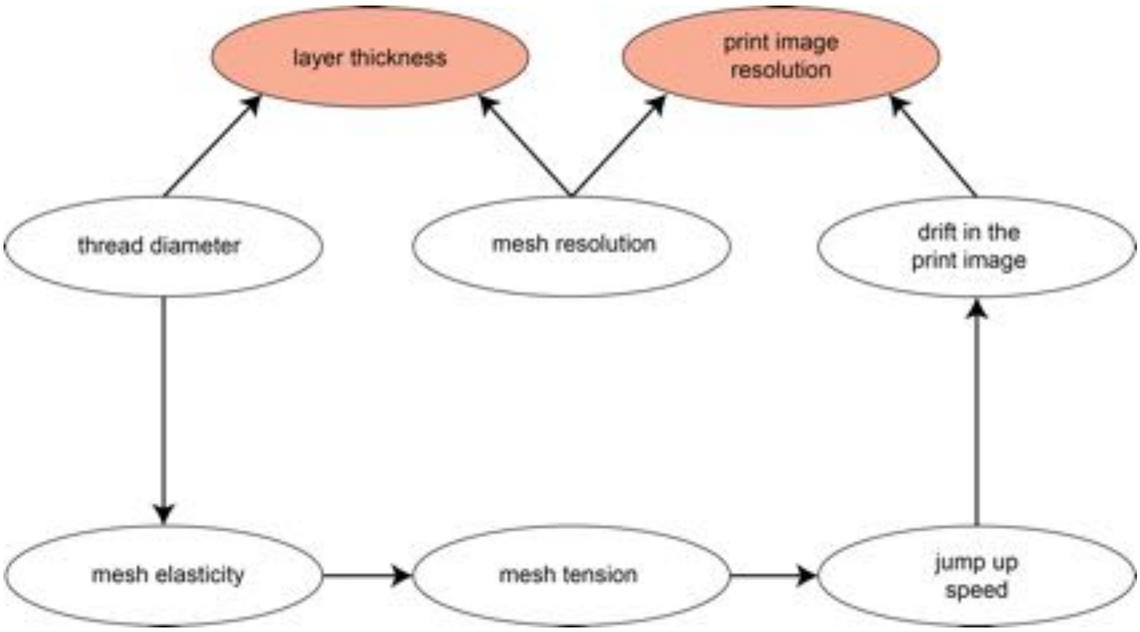


Figure 4.11: Varying mesh resolutions and the printing patterns, which result with increasing mesh resolution.

complete classification of the ink behavior on all possible substrates with all available net resolutions is beyond the scope of this thesis, we will show the general impact of different net resolutions as well as ink- and material properties on the print image.

In general, we have to distinguish between flat and rough surfaces of materials. Flat surfaces are optimal for screen printing, because the flat net can completely cover the whole substrate surface and uniformly apply the ink in the soaked net. A coarse surface makes it hard for the screen printing net to reach every part of the surface. Additionally, more ink is needed to fill a coarse surface completely without gaps. The general rule for the frame selection is therefore to use high net resolutions on flat surfaces and low net resolutions on rough surfaces.

As already mentioned, there are four types of ink involved, namely dielectric ink, silver nano-particle ink, transparent conductive ink and several phosphor inks. While the dielectric- and the silver nanoparticle ink were printable on all net resolution(only depending on the substrate roughness) that were available during our experiments (64T-120T), the transparent conductive ink and the phosphor ink showed limitations in their printability.

The transparent conductive ink shows, as many carbon-based inks, a high resistance after being printed. Since the ink should be as transparent as possible, the carbon particle density is as low as possible while still remaining conductive($\approx 50\Omega/cm^2$). This has an implication for materials with a high absorptivity like paper or wood. Since the ink does not remain on the surface of such materials but get sucked in, the density of the conductive particles decreases. It is therefore inevitable to print with low net resolutions on absorptive materials (<100T). For non-absorptive materials, we can observe a different behavior. Since the viscosity of the carbon-based ink is very low, it tends to smear easily on the substrate if the layer thickness is to high. It is therefore optimal for this ink to be printed with a high-resolution net (>100T). Unfortunately, such thin layers can only be printed on very flat substrates, where the net can reach the whole surface area. For rough surfaces, this cannot be accomplished, which leads to an inhomogeneous print with many gaps.

In contrast, phosphor inks show a similar viscosity as the dielectric and the silver nanoparticle ink, which makes them easily printable on many different substrates. Nevertheless, the maximal printable net resolution is restricted due to its particle size. As discussed in 3.3, the particle size of phosphor can vary between $2 - 50\mu m$ and the particles tend to stick together in bulks. This limits the maximal net resolution. Experiments with blue/green phosphor(Gwent C2061027P13) allowed to print at 120T while orange phosphor(Gwent C2070126P4) was only printable with 100T or less net resolution.

Screen Coating

After designing all necessary shapes for an electroluminescent display and choosing a proper screen printing frame, the next step in the fabrication is to apply a coating on the net. The purpose of such a coating is to seal these areas on the net, where no ink should reach the substrate. The remaining areas stay clean and let ink pass through.

The fabrication of such a coating can be divided into three methods. The first technique uses an adhesive foil(e.g. UlanoCUT Green). The print shapes are cut out of this foil manually or with an automatic plotter(e.g. Craft Robo 330-20). The processed foil can then be applied to the net. This method allows a very fast net preparation but also needs to deal with several drawbacks. Most importantly, it is difficult to cut out very fine details, which renders this method useless for high quality prints of electroluminescent displays.

In contrast to manual methods for coating a screen, it is also possible to fabricate a net fully automatic with a digital screen maker. The coating is applied on the net in a similar way as conventional ink-jet printers spray ink on paper. It is possible to reach very high resolutions up to $600dpi$ x $600dpi$(GOCCOPRO 100) and the fabrication of a screen happens within minutes. Even though such machines offer tremendous advantages in terms of speed and resolution, they are very expensive and often can only produce small net formats.

The third and most common method is based on photolithography. A photosensitive emulsion is applied on the net. By projecting the print shapes on the net, it is possible to represent very fine details in the coating. Since this method gives a very high quality in the final print and additionally is low-cost($\approx$ 10EUR per screen), we use this technique for producing electroluminescent displays during evaluation. Hence, we will describe this technique in more detail.

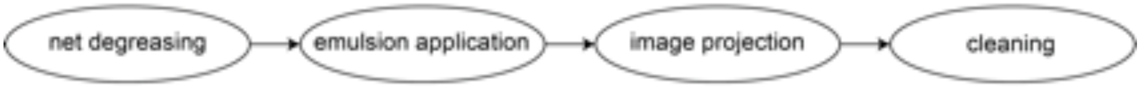


Figure 4.12: Pipeline to fabricate a net caoting.

Figure 4.12 visualizes the four steps in fabricating a net coating. At first, the net needs to be degreased. This is important to ensure the maximal conjunction between the photosensitive emulsion and the net. After the net is clean and completely dry again, the emulsion is applied on the net. To keep the photosensitive emulsion liquid, this step needs to be performed under yellow light. By moving on both sides of the net with a emulsion-filled groove from the bottom to the top with constant speed, the coating should be distributed on the net as uniformly as possible. The liquid coating is then dried with a heat gun or in a drying chamber. The emulsion becomes solid by this process but still remains water soluble.

The next step deals with projecting the designed shapes on the net. This is done by photolithography. After designing all necessary layers of an electroluminescent display in a vector-based program like Adobe Illustrator, these shapes are printed in black and white on transparent foil. It is compulsory that the printed shapes are completely opaque. The foil is then placed mirror-inverted on the coated net and irradiated with ultra-violet light. All areas of the net, which are hit by that light, become water insoluble, while the protected shapes can still be solved in water. The exposure time is dependent on the net type, the chemical properties of the emulsion and the intensity of the light source. In our experiments, the exposure time varied between 10-15 minutes.

Finally, the net is cleaned with water. Since the protected areas on the net are still water soluble, it is possible to wash them out completely. After drying the net again, it is ready to be used for screen printing.

Net Stringing

After preparing a net, each shape can be used only once for printing. Of course, the question arises how to recover a frame such that it can be used again. As already mentioned, the used functional inks are oil-based and can be removed by a thinner such as aceton.

Another way is to clean the net with a high pressure water cleaner. Both methods are time consuming and come with a large waste of chemicals and polluted water.

A fast and clean way to recover a frame is to simply cut out the used net and replace with a new one. This guarantees an absolutely clean mesh and comes with a tremendously smaller waste of chemicals and water. For that, a new net needs to be stringed on top of a frame and can then be glued with a strong two-component glue on it. Since the necessary net tensions are very high and thereby not feasible to be realized with pure muscular power of a human, it is necessary to use a stringing machine for this task.

Stringing machines are commercially available in all sizes and quality levels, but are very expensive. In our case, we decided to built up a custom stringing machine with materials from a hardware store less than 200 Euro(c.p. figure 4.13). The base construction consists of a double cross of solid wood bars, with clamps on each direction of the cross to put the net in and hold it. The clamps are attached on the cross with a double hook of variable length that can be altered by turning a rotatable middle threat. A screen printing frame is then placed in the middle of the cross such that each side of the frame points in the direction of the axis of the cross. A net is put over the frame and fixed inside the clamps with four screws each. The net is then stringed by turning the double hooks until the net has reached the desired tension. To attach the net permanently on the frame, a two-component glue is applied on the edges of the frame. After a hardening time of about one hour, the frame can be cut out of the machine and is ready for use.

Figure 4.13: Stringing a net on a screen printing frame. **Left:** The frame is placed in the middle of the machine with the clamps parallel to the frame edges. **Right:** The net is stringed with the clamps and then glued on the frame.

4.3 Power Supply

Electroluminescent displays are driven by alternating current of 200Hz - 1.5kHz and a voltage of 30V - 300V, which are the standard ranges to obtain long lifetimes and high brightness. For mobile applications a small driver IC(Durel D356B, sine wave, 220Vpp, 230Hz to 390Hz, 1V-7V DC Input) can be used to light up small segments up to several square centimeters area. For larger panels or high demands on the display brightness a stronger inverter can be used(Sparkfun DC12V10M, sine wave, 220Vpp, 800Hz - 3.5kHz, 0V-12V DC Input).

4.4 Safety

As for all electrical devices, it is recommended to insulate all open contacts of a display. This can be done with various tools like insulation spray or insulation tape. Additionally, it is recommended to integrate a current limiter into the power supply circuit as protection in case of an imperfect insulation.

4.5 Connecting Printed Electronics

In experiments with printed electroluminescent displays, it always arises the problem on how to connect a controller or a power supply with electrodes printed on paper or other materials. While approaches to solve this problem already exist[Shorter u. a. 2014], we developed several connectors especially to suited for printing on many materials.

Soldering
A standard technique to connect wires on circuit boards is to solder them on conductive pins. This technique can also be used for connecting electroluminescent lamps, if they are printed on heat-resistant materials like stone or metal. Since the solder becomes very stable and robust after cooling, this connector shows good durability properties. For materials, which burn or deform at $300C^{\circ}$ or less, this technique is not feasible, since the solder paste needs to be heated up to such temperatures in order to be melted.

Adhesive copper tape
To circumvent the direct application of high heat when soldering on a material, it is possible to solder a wire on an adhesive copper tape instead. This tape can then be glued on the printed electrode afterwards. Even though this connector offers the possibility to be applied on any material, it shows disadvantages in terms of durability. The adhesive tends to loose stability of time and medium mechanical forces can break the connector.

PCB connectors
Both presented connection methods are hard to remove from the printed electrode, are not reusable and are difficult to reconnect. To circumvent these disadvantages, we devel-

oped a multi-functional PCB connector that can connect on any material, is removable and can easily reconnect to another display.

The idea comes from circuit board design, where copper coated epoxyd plates are etched according to a predefined foot print. For creating a PCB connector, the foot print is designed in such a way that it has an optimal contact surface to the printed counter electrode. The wires on the PCB can then lead to pin holes, which can then be soldered directly on the epoxyd plate with removable and easily connectable jumper connectors(c.p. figure 4.14).

The designed boards then need to be attached on the printed electrodes of the display. For that, they can be integrated into a clip, if the display substrate material is thin enough for the clip. To enhance the connectivity at the contact areas of the connector, we applied small bulges of solder on the connectors. This increases the pressure of the connectors on the contact areas, which makes the clip more reliable. For thick substrates, the connector board can be glued with conductive adhesive(Bare Conductive COM-10994; 3M Z-Axis conductive tape 9703) on the display connectors. The jumper pins are thereby removable all the time, which makes an easy connection and separation possible.

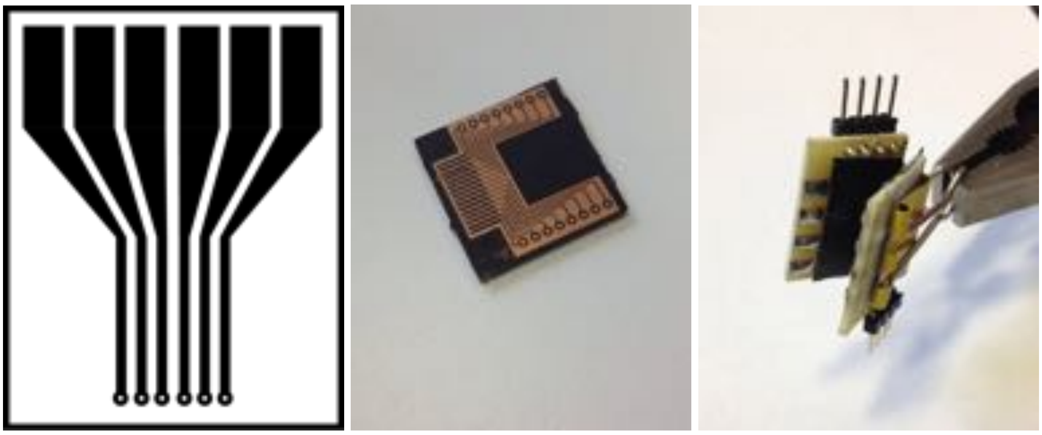


Figure 4.14: PCB Connector for printed electronics. **Left:** Schematic of a 6-pin connector. **Middle:** Coated epoxyd plate before etching. **Right:** Clip with solder buldges and jumper pins.

5 Sensing Framework for Thin Film Displays

In order to create interactive user interfaces, it is a key requirement to sense user input. This is of course also necessary for interactive displays. To this end, one typically has to add an additional sensing layer on top of a given display, e.g. as it needs to be done for printed LCD screens. In this chapter we will contribute a method that only uses the internal structure of an electroluminescent display to perform various sensing modalities *without* adding any additional layer to the screen. The idea is based on time division multiplexing and is able to add sensing capabilities to each printed display segment. We demonstrate this method with capacitive touch sensing and show the necessary circuitry as well as a physical implementation of the described principles.

5.1 Sensing Cycle

A method to add user input modalities to an electroluminescent display should fulfill several requirements. On the one hand, it should not need any additional layer to be printed on the display. Furthermore, the shape of the display should not be impaired by any distortion and no flickering of the display should be visible. To this end, we propose a time division multiplexing method(c.p. figure 5.1). The idea is to turn off the display for a very short time period. This time window is then used to perform sensing. Afterwards, the display is turned on again. If a certain frame rate is reached for a display, the sensing window is invisible for a human.

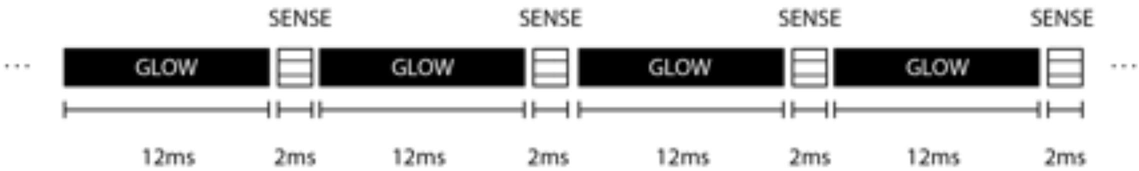


Figure 5.1: Time division multiplexed sensing cycle. The display is turned off for 2ms. This window is used for sensing.

In our experiments, we found a 2ms time frame for sensing a sufficient value. After that, the display is then turned on for 12ms before the sensing cycle starts again. This yields a refresh rate of $\approx 71Hz$, which is invisible for the human eye. Since the display is turned off for sensing, one has to expect a loss in brightness. For the given time frames, we encounter a loss of 14% brightness. Altering the sensing period or the activated display interval can vary the frame rate and the observable brightness.

An electroluminescent display consists, similar to a capacitor, of two parallel electrodes. Both electrodes needs to be set to high impedance and can then be used as a sensor. Many sensing methods support such a platform, e.g. touch sensing[Gong u. a. 2014; Rekimoto 2002; Gong u. a. 2011], proximity sensing[Gong u. a. 2014; Le Goc u. a. 2014] or deformation sensing[Gong u. a. 2014]. In the following, we will show the necessary circuitry and program code to realize capacitive touch sensing, exemplarily.

5.2 Implementation

Arduino Controller
In the following part, we will present several circuits that are used to insulate electrodes or turn devices on and off. A programmable controller that is necessary to operate these switches is the Arduino uno controller, which we used throughout our experiments. It offers twenty digital I/O pins that can be controlled by uploading compiled code or controlling the Arduino directly through serial communication.

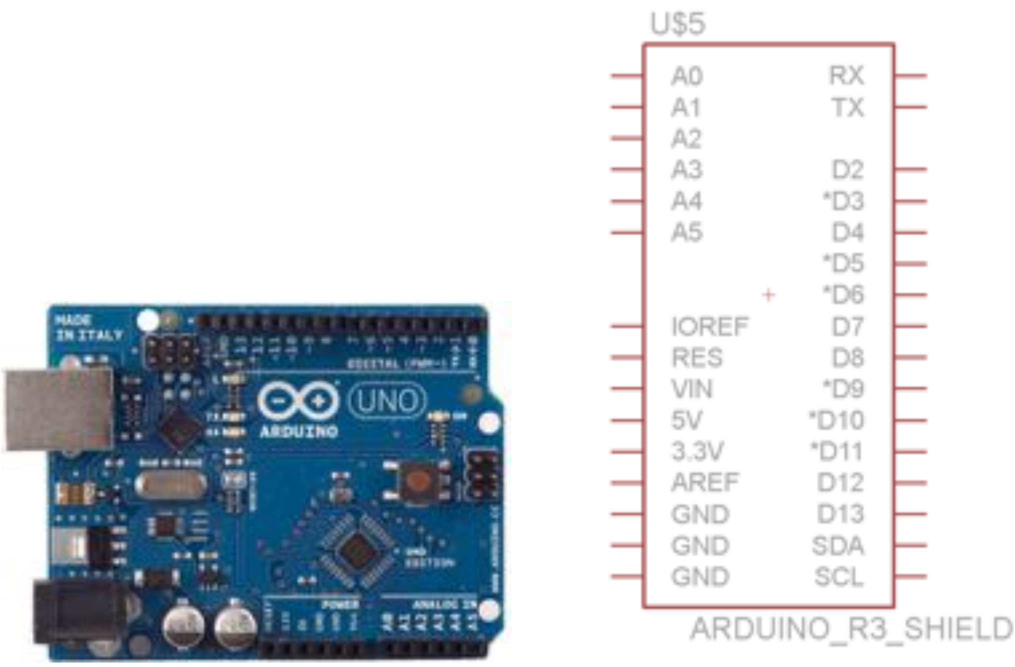


Figure 5.2: Arduino Uno. **Left:** image of an Arduino uno. **Right:** schematic of an Arduino uno. **Source:** http://www.arduino.cc

Touch Sensing Shield
As mentioned in the precious section, it is necessary to set the upper and the lower electrode of an electroluminescent display to high impedance in order to perform sensing.

Further on, it is inevitable to remove all loads from the electrodes to get rid of any electro magnetic field, since such a field can perturb the sensing values, especially for capacitive sensing. A straight forward implementation would isolate the electrodes with AC switches, since we drive the EL displays with 220V AC(c.p. section 4.3). Such switches are usually built with an optocoupler-triac circuit. The optocoupler acts as a signal donor and opens or closes the triac(c.p. figure 5.3). Unfortunately, such a circuit is not able to isolate the display electrodes completely from any electric field. Meassurements with an oscilloscope reveal that the circuits takes 150ms until all left over loads are discharged. Such a long waiting time would directly lead to an obvious flickering of the display and is therefore not feasible.

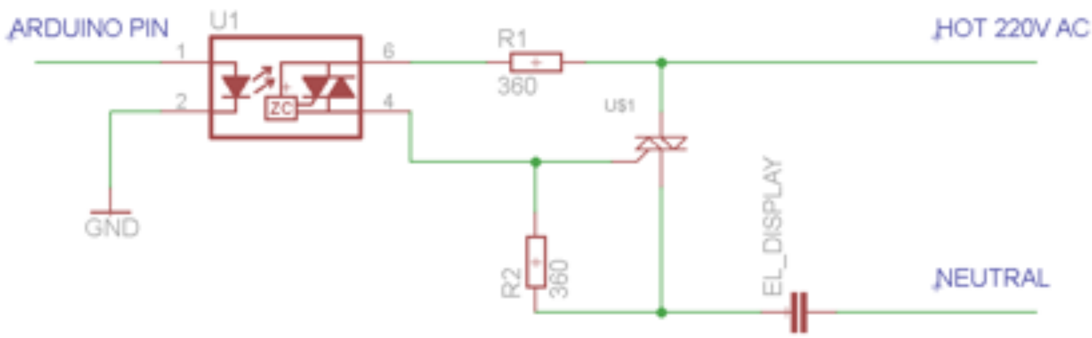


Figure 5.3: AC switch. Standard circuitry to turn on and off a device driven by alternating current based on an optocoupler-triac system. **R1,R2:** 360Ω resistor. **U$1:** Triac. **U1:** Optocoupler.

The next idea is to additionally deactivate the inverter during the sensing cycle. Since the used inverters take a DC power input, we need to build a transistor-based DC switch this time, which is slightly simpler than the already shown AC switch.

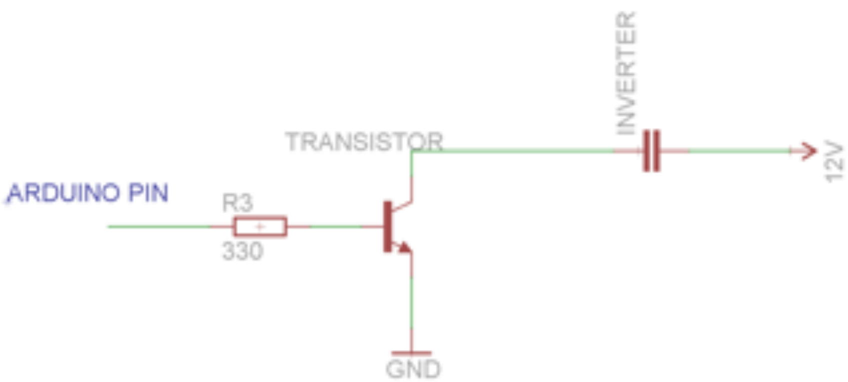


Figure 5.4: DC switch. Standard circuitry to turn on and off a device driven by direct current. **R3:** 330Ω resistor.

Again, the oscilloscope shows a large cool down time until the display electrode is complete discharged. This can be explained by the contained components of an inverter. Many inverter circuits use two large capacitors to transform DC to AC. These capacitors need a noticeable amount of time until they are completely discharged after turning them off. A method to reduce the cool down time below 1ms requires to neutralize the left over charges in the inverter directly. We therefore implemented a switch that creates a short cut between the plus- and the minus pole of the AC output of the inverter. After deactivating the energy supply of the inverter and isolating all display electrodes, we short cut the inverter to remove all left over charges. This strategy leads to extremely fast discharge times below 1ms and opens up the possibility to do sensing in less than 2ms.

To conclude the implementation part of this thesis, we developed a touch sensing shield that can control and perform sensing on a one segment EL display. The board is matched to the form factor of an Arduino uno such that it can simply be plugged onto it. It combines all mentioned techniques of the current section and can activate a flicker-free EL display with integrate capacitive sensing. The schematic of the board(c.p. figure 5.5) was transformed into a foot print, which was then ordered from a board manufacturer. After soldering all SMD components on the board, it was fully functional (c.p. figure 5.6).

The corresponding Arduino code controls the shield to send a binary signal over serial communication to a computer(1=touch, 0=notouch).

Listing 5.1: Arduino code for controlling the EL Touch Sensing Shield

```
#include <CapacitiveSensor.h>

CapacitiveSensor   cs_8_7 = CapacitiveSensor(8,7);

long value;
long alt_value;



boolean state;

unsigned long time;
unsigned long time2;

int threshold;

int wait_time;



void setup() {

```

```
pinMode(2,OUTPUT);
pinMode(3,OUTPUT);
pinMode(4,OUTPUT);
pinMode(9,OUTPUT);


Serial.begin(9600);

cs_8_7.set_CS_Timeout_Millis(5);

state  = true;
time = 0;
time2 = 0;

wait_time = 12;

}


void loop() {

digitalWrite(9,LOW);
digitalWrite(3,LOW);
digitalWrite(4,LOW);

delay(2);

digitalWrite(2,HIGH);

delay(3);

alt_value  =  cs_8_7.capacitiveSensor(10);


if((millis()-time)>400)
  value  =  alt_value;

else
  value   = 0;

digitalWrite(2,LOW);

delay(1);

if(state) {
  digitalWrite(4,HIGH);
```

```
    digitalWrite(3,HIGH);
    digitalWrite(9,HIGH);
  }

  //Serial.println(alt_value);


  if(state)
    //threshold when display on.
    threshold = 30;

  else
    //threshold when display off
    threshold = 16;


  if(value>threshold) {

  //switch display
  if(state)
    state = false;
  else
    state = true;

  time = millis();

  }

  if((millis()-time2)>100) {

  //send status
  if(state)
    Serial.print(1);
  else
    Serial.print(0);
    time2 = millis();
  }

  delay(wait_time);

  }
```

5.3 Evaluation

To show the difference in the discharging times between several circuits, we conducted two experiments with a Picoscope 6402 A oscilloscope. We use the EL Touch Sensing Shield and change the code in such a way that pin 2, responsible for creating a short cut in the AC output, is never activated in the first experiment. In the second experiment, it is activated 1ms after the sensing cycle starts. This is because, we want to make sure that the DC switch has closed the energy supply for the inverter completely.

As one can see in the first experiment, the cool down time for the sensing cycle is at 80ms until the voltage level has reached the zero line(c.p. figure 5.7). Such a long turn off time for a display is not acceptable for creating a flicker free appearance. In the second experiment, we observe a instantaneous drop to the zero line, when the inverter is shortcutted.

Besides this technical evaluation concerning the sensing cycle, we produced five application cases, which show the usefulness and the applicability of the presented input modalities, which we present in chapter 6.

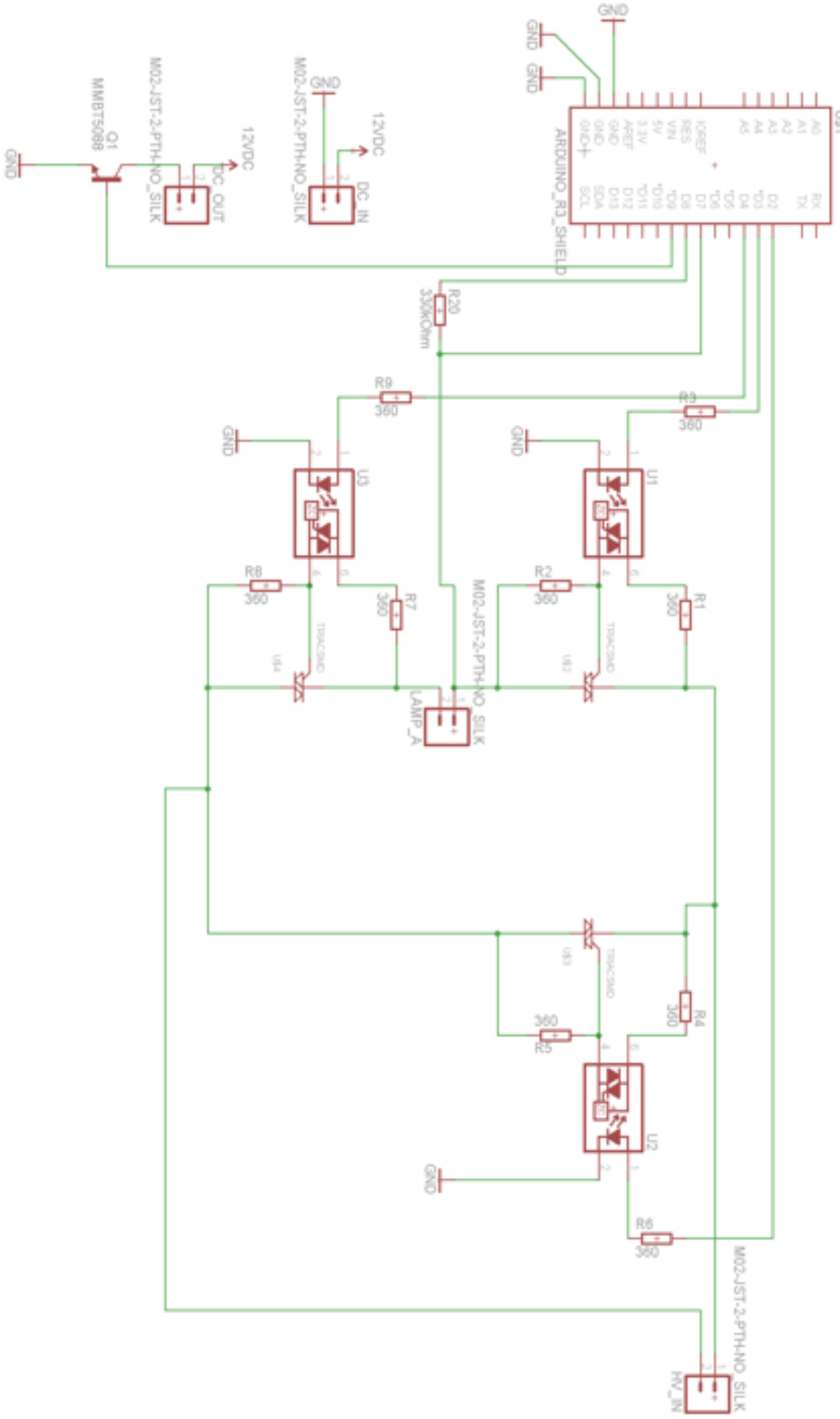


Figure 5.5: EL Arduino shield for controlling a one segment display with combined touch sensing.

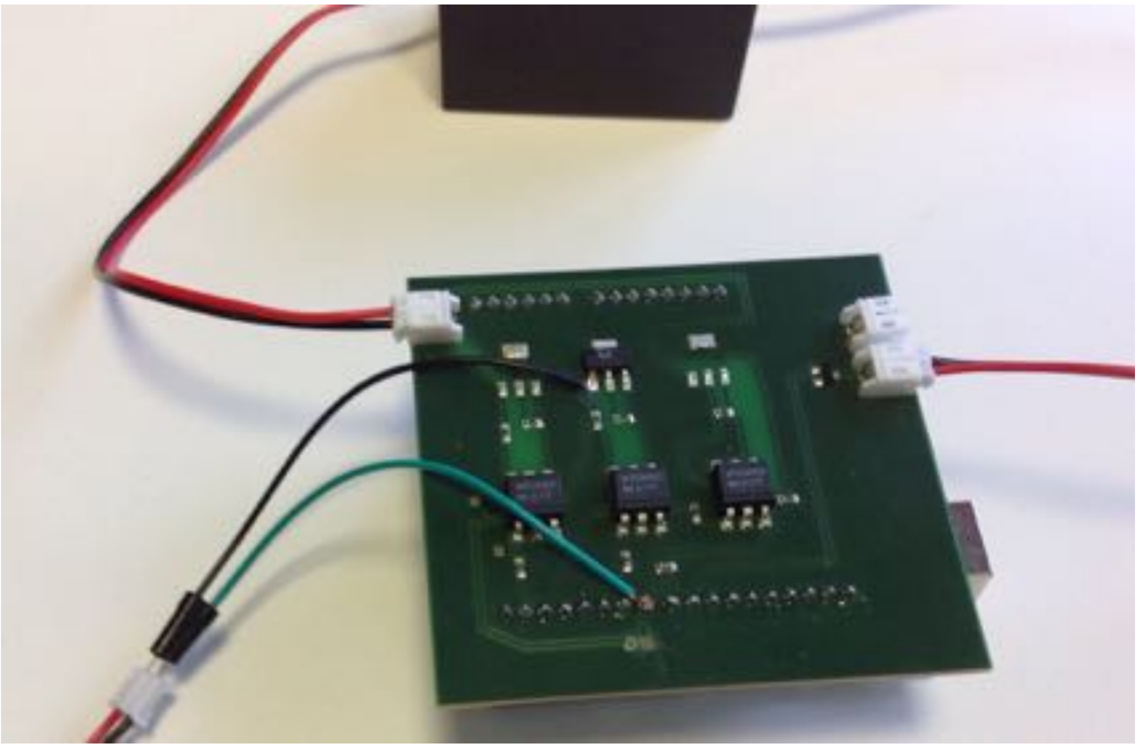
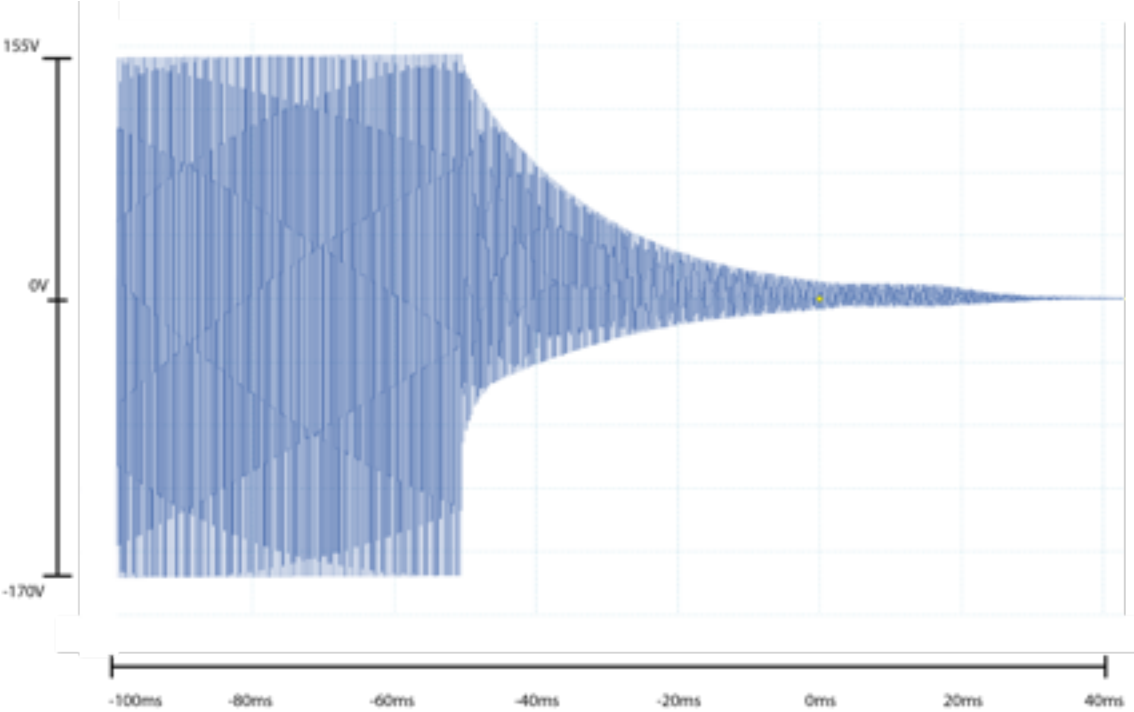


Figure 5.6: Touch Sensing Shield. The circuit uses an external inverter and can control one segment of an electroluminescent display. Additionally, it can perform touch sensing and sends the collected data to the Arduino controller.



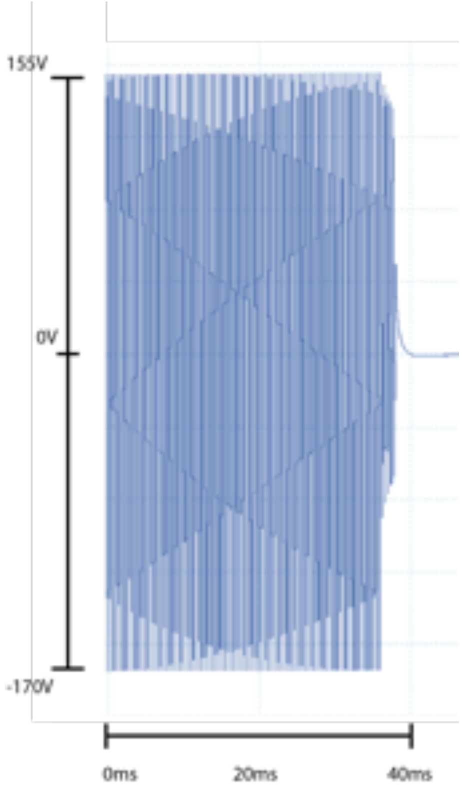


Figure 5.7: Oscilloscope images of the sensing cycle. The display gets deactivated, when the voltage drops. **Upper:** The display electrodes get isolated and the inverter gets deactivated. The voltage drops at t=-50ms. As one can see, the electrode needs ≈80ms to fully decharge. **Lower:** The display electrodes and the inverter get deactivated as before, but additionally, the inverter is shortcutted after 1ms. The voltage drops instantaneously and releases the electrode for sensing.

6 Application Cases

To evaluate the presented fabrication pipeline and the sensing framework, five application examples of printed displays have been implemented as part of this thesis. They demonstrate the possibilities and the potential for user interface design in various areas like ubiquitous, mobile and wearable computing.

Figure 6.1: Examples of electroluminescent displays. **Upper Left:** Interactive paper postcard. **Lower Left:** Awareness Flower. **Upper Middle:** Matrix Pong Game. **Lower Middle:** Integration with printed electronics. **Right:** Interactive watchstrap. **Source:** [Olberding u. a. 2014]

Interactive watch strap

Electroluminescent displays are well-suited for wearable device. This example shows a notification display that naturally blends into the design of a watch. The display is printed on transparent PET film and is integrated into the watch strap.

Interactive paper postcard

This example shows the great possibilities of interleaving traditional print and interactive displays. The paper print-out shows an image of a car with two buttons on the bottom of the figure. Pressing these buttons activate displays on the image that were printed on the backside of the paper, glowing through the substrate. We show here the high edge resolution that is possible with this fabrication method and demonstrate the applicability for augmented paper.

Printed matrix ping pong
Matrix displays are especially well suited to visualize dynamic content. We show here an interactive pong game that was realized with a 16x16 pixel matrix and can be controlled with fast response times via two touch buttons.

Awareness flower
In this example, we printed an artistic phone symbol on the backside of the flexible leaf of an artificial plant. The segments is invisible, while it is unused but lights up, to notify the user of e.g. incoming mail or a phone call. We show here the seamless integration of ubiquitous computing into the environment.

Integration with printed electronics
In the last application case, we show the simple integration of flexible displays into printed electronic circuits. The bottom layer of the display is extended to connect additional electric components like LEDs or transistors. Here, a physical bend sensors increments the visualized number on a 7-segment-display.

7 Conclusion

In this thesis, we presented a fast and inexpensive fabrication method to produce thin, flexible and custom-shaped electroluminescent displays based on screen printing. This method do not require a high-end lab with expensive machinery and expert knowledge, but is well suited for print shops or even the fabrication at home. It is furthermore possible to choose from a large variety of materials to print on and the designer can choose from a wide palette of available colors. Besides the printing pipeline, we additionally contribute an integrated sensing framework. This sensing concept uses the internal structure of the display itself as the sensor and is capable of supporting a variety of sensing modalities like touch sensing or proximity sensing. We demonstrated the usability of this technology with a selection of five application cases that show the manifold of possibilities that come up for ubiquitous, mobile and wearable computing.

A Appendix

A.1 ACM UIST 2014 full paper publication

PrintScreen: Fabricating Highly Customizable Thin-film Touch-Displays

Simon Olberding, Michael Wessely, Jürgen Steimle

Max Planck Institute for Informatics and Saarland University
Campus E1.7, 66123 Saarbrücken, Germany
{solberdi, mwessely, jsteimle}@mpi-inf.mpg.de

Figure 1. PrintScreen contributes a digital fabrication approach to enable non-experts to print custom flexible displays. They can be fully folded or rolled and enable manifold applications in ubiquitous, mobile and wearable computing.

ABSTRACT

PrintScreen is an enabling technology for digital fabrication of customized flexible displays using thin-film electroluminescence (TFEL). It enables inexpensive and rapid fabrication of highly customized displays in low volume, in a simple lab environment, print shop or even at home. We show how to print ultra-thin (120 µm) segmented and passive matrix displays in greyscale or multi-color on a variety of deformable and rigid substrate materials, including PET film, office paper, leather, metal, stone, and wood. The displays can have custom, unconventional 2D shapes and can be bent, rolled and folded to create 3D shapes. We contribute a systematic overview of graphical display primitives for customized displays and show how to integrate them with static print and printed electronics. Furthermore, we contribute a sensing framework, which leverages the display itself for touch sensing. To demonstrate the wide applicability of PrintScreen, we present application examples from ubiquitous, mobile and wearable computing.

Author Keywords

Flexible display; Thin-film display; TFEL; Electroluminescence; Printed electronics; Digital fabrication; Rapid prototyping; Touch input; Ubiquitous Computing.

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INTRODUCTION

Printed electronics is becoming a powerful and affordable enabling technology for fabricating functional devices and HCI prototypes that have very thin and deformable form factors. For many years already, printing has been a powerful means allowing end-users to produce customized *static* print products rapidly, inexpensively and in high quality. Recent work has contributed methods for easily printing custom *interactive* components on thin and flexible substrates. While sensing of user *input* has been successfully demonstrated [7, 13], it has not been possible so far to print customized flexible *displays* rapidly and inexpensively. Printing flexible displays, such as OLEDs or Electronic Paper, required a high-end print lab, complex machinery and expert skills, making it prohibitive to fabricate custom displays in low volume.

We present PrintScreen, a versatile platform that enables non-expert users to design and fabricate highly customized flexible interactive displays. The displays are technically based on thin-film electroluminescence (TFEL).

The platform proposes a novel perspective on displays: instead of buying an off-the-shelf display, the designer can create a custom digital design, which meets the specific demands of the application, and then simply print the display. Printing customized flexible displays empowers makers and designers to create customized interactive print products, digital signage, smart objects, personalized computing devices and crafts with embedded display. For HCI researchers and practitioners, this is a powerful enabling technology for mobile, wearable and ubiquitous computing interfaces. It enables rapid and high-fidelity prototyping of functional HCI devices with embedded displays of highly custom shapes, on deformable and on unconventional materials.

Based on a holistic five-dimensional view on customized displays, we present the following main contributions:

1) We present *two methods for non-expert printing* of customized thin-film displays, using either screen printing or conductive inkjet printing. The approach is rapid, inexpensive, and does not require much hardware nor technical knowledge. Despite the restrictions stemming from manual fabrication, the display features a high luminance, is only 120 µm thick, bendable, fully rollable, and even foldable at arbitrary positions. It can contain custom-defined high-resolution segments (resolution of contours comparable to 250 dpi laser print) and/or a low-resolution passive matrix (up to 30 pixels per inch). Each segment or pixel can have a color defined at design-time from a wide palette of possible colors. At run-time, it has adjustable brightness intensity. We show that the display can be printed on a *large variety of substrates*, such as paper, plastic, leather or wood, making it ideal for mobile, embedded and wearable applications. PrintScreen can be used to fabricate displays of *irregular and unconventional shapes,* including 2D shapes, folded 3D shapes and adaptable shapes.

2) We propose a digital design approach for displays, which is based on conventional 2D vector graphics. We contribute the first systematic overview of *display primitives* for user-printed displays, which act as basic building blocks in the graphical design. Moreover we show how to integrate printed display primitives with static printed artwork and with printed electronics.

3) We contribute a *sensing framework*, which allows using the printed TFEL display itself for a variety of input sensing. We demonstrate this principle for integrated touch sensing.

To demonstrate how PrintScreen can be used and to show its wide applicability, we present five *example applications* from ubiquitous, mobile and wearable computing. Results from a technical evaluation show that the displays are bright and very robust to bending and folding. We conclude by discussing benefits and limitations of PrintScreen.

RELATED WORK

Digital Fabrication of Electronics

An emerging body of related work is demonstrating the potential of printed electronics for applications in Human-Computer Interaction. Midas [30] introduced a platform for fabricating custom circuits to sense touch input, based on vinyl cutting. Kawahara et al. [13, 14] introduced conductive inkjet printing with an off-the-shelf printer as an instant means for printing customized sensors and antennae. This approach was also used for flexible multi-touch sensor sheets [7, 14]. Pyzoflex [27] leverages printed piezoelectric elements to capture pressure and temperature on a thin sheet. Poupyrev et al. [12] have shown how printed conductors can capture user-generated energy. This body of previous work did not address visual output.

Thin-film Display Technologies

Organic light emitting diodes (OLEDs) and electrophoretic displays (electronic paper) can be printed on flexible substrates. Both technologies enable high-resolution displays, in addition OLED displays support a wide color spectrum. However, they are still complicated to produce. For instance, an OLED display typically requires six layers [15]; moreover it is very sensitive to oxygen during fabrication and requires proper permanent sealing during use. Therefore, a high-end print lab environment is required. While rollable and fully foldable OLED and electronic paper displays have been demonstrated as prototypes, they are not commercially available yet.

Thermochromic [19] and electrochromic [3] displays are less complicated to manufacture. However, they have very long switching intervals and precise control of thermochromic displays is challenging, as the ink is influenced by the ambient temperature.

Electroluminescent (EL) displays are very robust, have fast switching times and a long lifetime of up to 50,000 hours [6]. Therefore the technology is often used for lighting applications [4, 21]. Inspired by [4, 35], we propose electroluminescence for custom-printed displays. The technology, a simple form of OLED, is based on phosphoric inks, which act as luminescent material. The print process requires only 4 layers [15]. Recent chemical advancement allow for inks that can be easily processed and need low curing temperatures. EL displays require higher AC voltages but very little current to operate. Previous work proposed creating simple EL displays by cutting out segments from an EL film [2]; in contrast, our approach relies on high-resolution printing and therefore enables fabrication of a much wider spectrum of displays.

A substantially different approach is based on 3D printed optics [36]. Printed light pipes transmit light from a conventional rigid display to custom points on the surface of a 3D printed object. This allows for easily designing 3D shaped displays of custom shapes, supporting full color and a high resolution. However, designed for 3D printing the approach is not compatible with thin-film form factors, since the printed optical elements need some volume.

Applications of Deformable and Custom-shaped Displays

A body of work demonstrates the need for objects that are augmented with interactive displays of different size and shape [10, 16, 23, 24, 34, 37], resolution [9, 24] and substrate [24]. One stream of research proposes deformable displays of various shapes and sizes for use in mobile and wearable contexts [5, 17, 20, 25, 31, 33, 37, 29]. Another stream investigated projection-augmented paper prints [16, 18, 34], even in large poster sizes [36]. Work on interactive paper origami proposes manually attached LEDs as active output on folded paper objects [24]. Prototypes from previous work use projection, tiled rigid displays or rectangular flexible displays on plastic substrates. The PrintScreen plat-

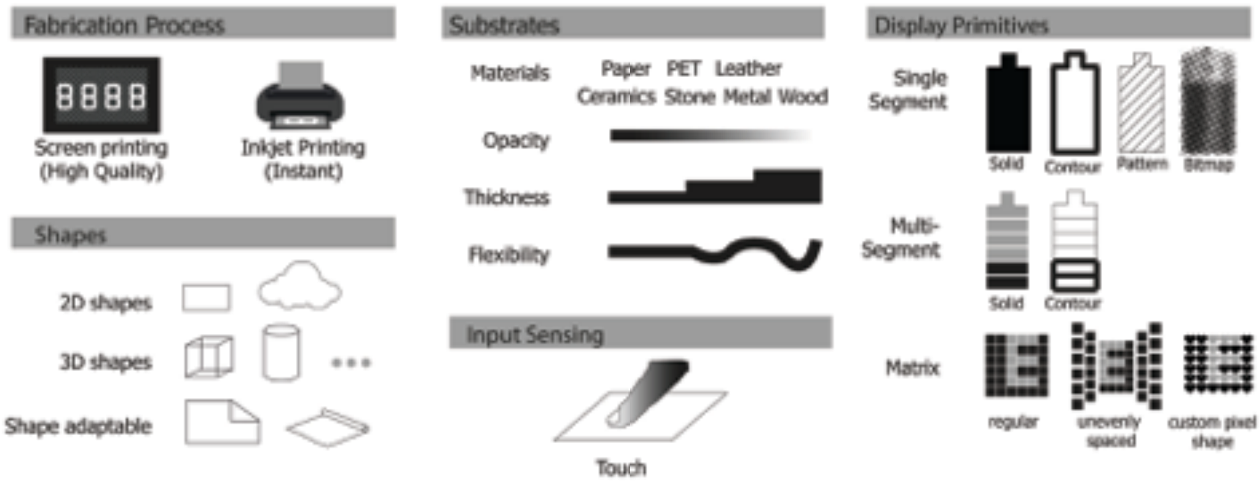

Figure 2. Five-dimensional design space for digital fabrication of customized displays.

form opens up substantially more degrees of freedom in designing custom displays for HCI prototypes.

DESIGN SPACE OF CUSTOMIZED DISPLAYS

Custom-made displays open up considerably more degrees of freedom for the design than off-the-shelf displays. We identified five key dimensions for digital fabrication of customized displays, which systematize the design options. This section provides an overview of these dimensions, which form the foundation of the PrintScreen platform. The design space is illustrated in Fig. 2.

Fabrication Process: How to print

We propose a digital fabrication approach for production of customized displays. The designer generates a digital model of the display and then prints this model. Ideally, printing is as instant and easy as sending a document to an office printer. This would enable prototyping with rapid and many design iterations. We introduce an instant fabrication process based on conductive inkjet printing, which comes close to this ease of fabrication. Moreover, we propose a second fabrication approach, which requires screen-printing on a beginner's level. While it takes longer to fabricate a display, it is of higher quality and supports the full set of substrate materials, display primitives and sensing modes presented in this paper.

Substrate Materials: On what to print

Customized displays may be printed on various materials that vary in thickness, flexibility, texture and opacity. PrintScreen supports many substrate materials, including highly deformable and foldable office paper, transparent or nontransparent PET film, leather, wood, ceramics, stone (marble) and metal (steel). The display adds only 110 µm of thickness to the base substrate.

Display Primitives: What to print

Customized displays offer a large variety of design options regarding the display contents, far more than the regular matrix which one would intuitively think of. If contents are known at design time, segmented and multi-segmented displays are a compelling option. They feature very sharp contours and homogeneous fill, even if printed in large sizes, while nevertheless being easy to control. In addition, we introduce segments that feature an arbitrary bitmap pattern which is defined at design-time. For very dynamic applications, matrix displays are the preferred option. PrintScreen allows for printing conventional matrices in a custom resolution, but adds options for customization by offering unevenly spaced matrices and pixels in custom shapes.

Display Shapes: What form factors are possible

A key question for any application is the size and shape of the display. With off-the-shelf displays, the designer has relatively little choice. Non-rectangular outlines, extreme aspect ratios, curved or 3D shapes are typically not available. However, such non-standard shapes are important to make an embedded display fit within an object or the physical environment. PrintScreen offers the designer a much higher degree of design flexibility. It supports custom 2D outlines; moreover it enables custom 3D shapes, which are created by bending and folding. Moreover, displays can be made shape-adaptable and resizable, using bending, folding or rolling, but are not stretchable.

Integrated Input Sensing: How to interact

User input is a key property of interactive display surfaces. We contribute a generic platform for sensing of user input, which is directly integrated with the printed display. As examples we demonstrate touch input.

In the following main part of the paper, we will discuss each of these dimensions.

FABRICATION PROCESS

We contribute two approaches to allow non-experts to fabricate customized thin-film electroluminescent displays: a high-quality and an instant process. Both are easy to learn and perform for non-experts and require only off-the-shelf tools and consumables.

Printed Electroluminescent Displays

Thin-film electroluminescent displays actively emit light. A segment of a TFEL display consists of two overlaid electrodes, which act as a capacitor. Inside the capacitor is a

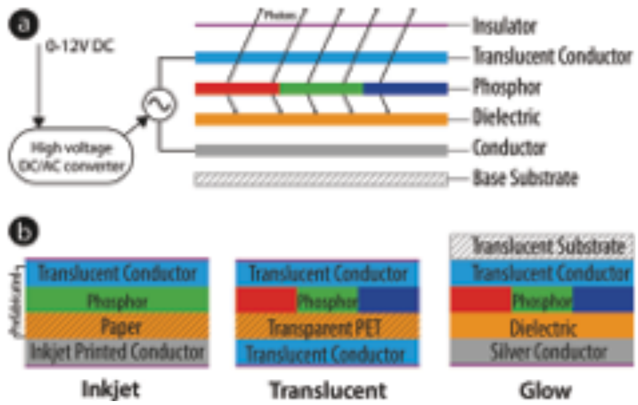

Figure 3. a) Composition of the printed layers of an electroluminescent display: Silver Conductor (C2131014D3, 100mΩ/sq), a barium titanate based dielectric (D2070209P6), phosphor (e.g. C2101125P4) and a PEDOT based translucent conductor (D2070209P6, 500-700 Ω/sq). b) Variations of the standard structure to create translucent displays, display glowing through materials or inkjet-printable displays.

layer made of phosphor and a dielectric layer. If a high voltage, low current AC signal is applied, the phosphor emits photons (see Fig. 3 a). TFEL displays are used in many commercial products, e.g., as backlight for car dashboards.

Digital Design

The designer of the display first creates a digital design in a standard 2D vector graphics editor, such as Adobe Illustrator. Each segment or pixel is created as if it was ordinary visual artwork, using the application's tools for creating lines, polygons, text, fills, etc. Hence, designing an interactive display is pretty much comparable to designing conventional 2D graphics.

For screen printing, the designer generates four adjacent identical copies of the design – one for each print layer (see Fig 3). If segments and pixels shall be printed in more than one color, one more layer is added for each additional color. Laying out the copies adjacently allows to create one single print mask that contains all print layers, making screen printing cheaper and faster. For inkjet printing, only one copy is required. Next, the designer lays out the wires that are required for controlling the segments. The minimum width is 300 µm. On the first copy (bottom electrode), each segment is connected with an individual input pin. For screen printing, all segments on the fourth copy (top electrode) are connected to a shared ground pin. Alternatively a grid of segments or pixels can be wired as a matrix.

Screen Printing for High Quality

For screen printing, we used off-the-shelf equipment for hobbyists (approx. 200 €). We follow a standard multi-layer screen-printing process [22], which is commonly used for printing on paper or on fabrics and can be easily learned by non-experts. Each layer of the display stack is printed successively, from bottom to top. Details on the inks, available

Figure 4. Dual sided print on office paper

colors, mesh density of the screen and the instructions of use can be found in [8]. For multi-color displays, two or more layers of differently-colored phosphor are printed. Finally, the top layer is insulated with acrylic insulating spray (dielectric strength 80kV/mm). Overall, the display adds 110 µm to the substrate. We successfully printed a display on a 10 µm thick PET film (Gwent, F2111117D1), resulting in 120 µm as the minimal thickness of the final printed display. To create a dual-sided display (see Fig. 4), the same process can be repeated on the reverse side of the substrate.

Segments can be printed in a resolution of up to 30 lines per inch (lpi). As a rule of thumb, this corresponds approximately to 60 pixels per inch (ppi). For comparison, a conventional office laser printer has between 35 ppi (300 dpi) and 75 ppi (600 dpi). We use printed guidelines to improve inter-layer alignment. However, the manual printing process introduces an offset between individual layers. We analyzed 10 display samples and measured the maximum offset between individual layers. We found the designer can ensure the full segment be functional by enlarging the top and bottom electrodes as well as the dielectric by 300 µm to each side.

Printing of the application examples presented in this paper took one person between two and four hours. The time depends not on the complexity of the display contents, but on the display size and the number of different colors. The cost

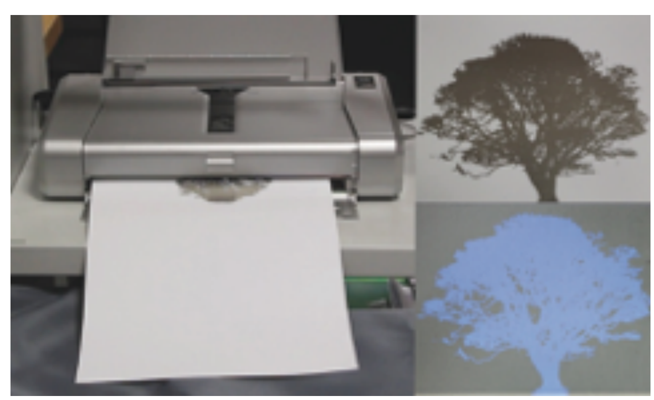

Figure 5. Instant inkjet printing. A printed electrode (left, upper right) is illuminated (lower right).

of consumables for printing a completely covered A4-sized display is approx. 2 € for the screen mesh and 19 € for the inks. Many applications require segments only on some locations on the substrate, which can further reduce cost quite considerably.

Conductive Inkjet Printing for Instant Fabrication

The second fabrication process ensures instant fabrication, which is important for design iterations in rapid prototyping. No screen print equipment is required. However, it offers fewer design options.

The designer uses a prefabricated display film (Fig. 3b and Fig. 5). This film contains all printed layers except the bottom electrode. It consists of a sheet of coated paper (Mitsubishi NB-WF-3GF100), which acts as substrate and dielectric. On top of it, a fully filled layer of phosphor (in one color) and a fully filled layer of transparent conductor is printed. This film can be fabricated in bulk using screen printing, as describe above; in the future a paper manufacturer could make it commercially available for purchase.

The designer uses conductive inkjet printing [14] to print the digital design (aka. the bottom electrode layer) on the reverse side of the prefabricated display film. We use an off-the-shelf, consumer-grade inkjet printer (Canon IP-100) with Mitsubishi NBSIJ-MU10 silver ink. Finally, to seal the bottom electrodes, insulating spray is applied, or a thin layer of dielectric (e.g. office paper) is glued or laminated onto the reverse side of the display.

In the prefabricated film, the top electrode, phosphor and dielectric cover the entire surface. This restricts what types of display can be realized. In particular, the display is unicolored. Only segments, but no matrix can be designed. Segments always have a solid fill, and wires used for tethering the electrodes with the controller light up on the display. Touch sensing is restricted to a single touch contact on the entire display. However, contours and surface patterns can have a high resolution, which is defined by the resolution of the inkjet printer (600 dpi).

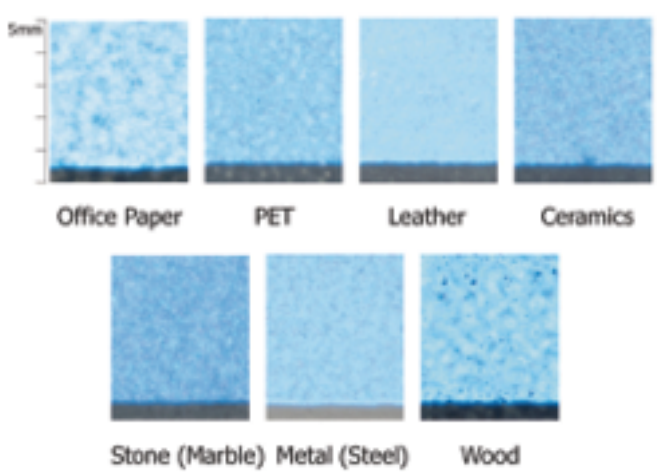

Figure 6. Enlarged view of an illuminated segment and its contour, printed on various substrates.

Controller

To light up a display segment, the controller applies a high-voltage, low current AC signal between the upper and lower electrodes. The luminance of a display segment or pixel is controlled using pulse-width modulation, a standard method for controlling the luminance of LEDs.

For mobile applications, our prototypical controller uses a small driver IC (Model Durel D356B, sine wave, 220 Vpp, 230Hz to 390Hz). This driver IC generates the high-voltage AC signal from a 1.0-7.0V DC power source. If a higher luminance is required, a stronger 0-12.0V driver IC with a slightly bigger footprint can be used (Model Sparkfun DC12V10M, sine wave, 220Vpp, 800Hz to 3.5KHz). A microcontroller (ATmega2560) triggers optocouplers (MOC3063) for multiplexing the high-voltage signal between display pins.

The TFEL-specific ghosting effect in passive matrix displays can be significantly reduced by using a slightly modified controller design [11], thus further increasing the contrast of the matrix. To interface the display with the controller, we solder copper wires onto printed pin areas. For a larger number of pins, a flat-ribbon cable and 3M Electrically Conductive Adhesive Transfer Tape 9703 can be used.

The number of output pins of the internal microcontroller restricts our controller to up to 40 separate segments or a 20x20 matrix with passive matrix time-division multiplexing. However, the number of segments or pixels can be substantially increased by using multiplexers to increase the number of output pins of the microcontroller and additional optocouplers to switch high voltages. To keep the size of the controller (currently 5x7cm) small, small optocouplers (TLP266J) can be used.

Despite high voltages, the approach is safe and energy efficient, and even usable for fully mobile applications, because the current is very low and the TFEL display is very energy efficient (2.6 mW/cm^2 in highest luminance, using DC12V10M). The inkjet method uses a thicker dielectric; therefore power consumption increases to 38 mW/cm^2.

SUBSTRATE MATERIALS

For applications in ubiquitous, embedded and wearable interaction, it is of high importance that the display can be integrated with a variety of materials. Our screen printing approach allows for printing the display right onto the substrate material, integrating it fully with the object and making additional carrier materials and lamination obsolete.

We successfully printed displays on a wide variety of materials, including highly flexible, translucent and transparent materials (see. Fig. 6). Among them was office paper, PET, leather, ceramics, marble, steel and untreated wood. Figure 6 shows that the surface structure, contours and color saturation of an illuminated display segment varies depending on the material; the contours of the printed segment are more or less crisp.

We experienced that successful prints largely depend on the (ideally high) smoothness of the material's surface, leading to a homogenous display surface and crisp contours. We could not print on extremely uneven surfaces, such as cotton fabrics or suede leather. But we could successfully print on quite porous materials, such as office paper and untreated wood, with some decrease in homogeneity and crisp contours. In our experience the absorbency of the material is not decisive: we could print even on steel and stone in a very high quality.

Since the phosphor inks are not transparent, printing on the material inherently changes its visual properties. To fully hide the display components, the display can be printed on the reverse side of translucent materials. We also successfully printed the display on the backside of translucent materials, such as PET (see Fig. 8), paper (see Fig. 9), and wood veneer (see Fig. 6 lower right).

DISPLAY PRIMITIVES

Custom displays come in a large variety, ranging from easy to control segmented displays to highly generic matrix displays. In this section, we contribute a systematic overview of display primitives, structuring known primitives and contributing new ones. This acts as a graphical inventory from which the designer can combine elements to design the visual contents of the display. As PrintScreen applies principles from 2D vector graphics for the digital fabrication approach, the designer has extensive design flexibility and can make use of the powerful tools of modern vector graphics editors.

Single Segment

A single segment features an area or a contour, or a combination of both. A TFEL display homogeneously lights up the element, even over a large surface area. A segment features sharp contours, even if printed in large size. A segment can be printed with a high resolution of 60 ppi with screen print and 75 ppi with conductive inkjet print.

We contribute over previous work on display segments by allowing the designer to very flexibly vary the shape, the fill and the contour of the segment in the digital design. This is illustrated in Figure 7. The fill can be either *empty* (not lighting, fully transparent), *solid* (lighting homogeneously in one color), can contain *line art or line patterns* as a visible structure, or can show a predefined greyscale *bitmap image*. For bitmap images, we use half-toning, a method that produces greyscale with one color by printing dots of different density and size on the substrate.

A non-solid fill is realized as follows: like for a solid fill, the top and bottom electrodes and the dielectric are kept solid, covering the entire area of the segment. In contrast, phosphor is printed only at locations that should light up, i.e. lines for line patterns or dots for half-toning. In our experience modifying the phosphor layer is preferable to modifying one of the electrode layers, as the former approach ensures that the full electrode remains conductive, independently of the pattern.

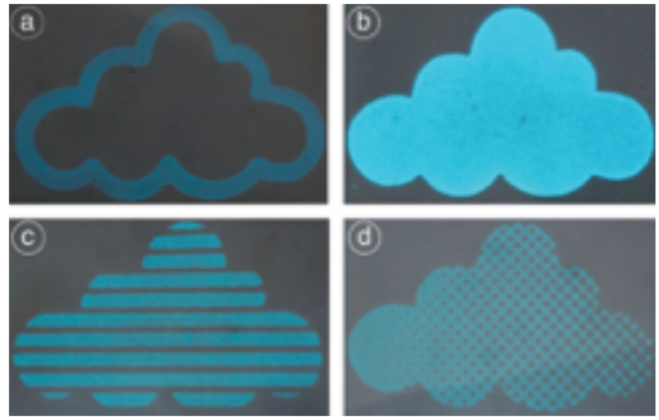

Figure 7. Display segments: (a) contour, (b) solid fill, (c) line pattern fill, (d) bitmap fill.

The contour of a segment can be solid or made of a dashed pattern. If realized as two separate electrodes, contour and filled area can be separately controlled. Displayed dots should have a minimum diameter of 300 microns.

Multi-Segment

A multi-segment splits a single segment up into several sub-segments that can be independently controlled. Examples include a seven-segment display for numerical values or a progress bar. The principles introduced for single segments fully apply to multi-segments.

Matrix

PrintScreen supports printing a regular matrix display (Fig. 8a). We print the rows of the matrix as the bottom electrode and the columns of the matrix as the top electrodes. The phosphor layer and dielectric are continuous. Time-multiplexing between rows and columns allows for addressing individual pixels. The designer can define the size of the matrix and the pixel density. The maximum density is defined by the resolution of the screen printing equipment,

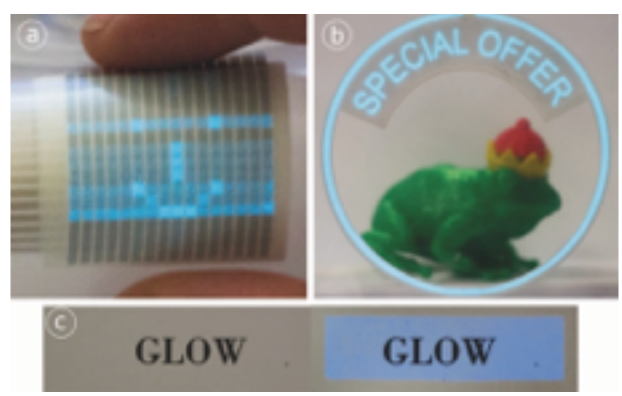

Figure 8. a) Passive Matrix Display. b) Translucent displayed on transparent PET film, in front of an object. c) Integration with laser-printed static visuals.

in our case 30 parallel lines per inch, leading to 30 pixels per inch.

We extend the design possibilities for matrix displays in two ways: (1) *Unevenly-spaced and -sized pixels* allow for varying the information density, e.g. higher resolution in the center and lower resolution in the periphery of a display. (2) *Custom-shaped pixels* allow for creating a unique visual appearance of the display, e.g. for digital signage or artistic installations. Both these options come at virtually no extra cost, as it is very easy to modify these parameters in the digital design.

Translucent Display Segments

To fabricate translucent display segments, the back electrode is printed with translucent conductive ink on the reverse side of a transparent PET film (see Fig. 3b). The film itself acts as the dielectric, eliminating the need for non-transparent dielectric ink. The phosphor and top electrode layers are printed on the front side. The conductor and phosphor inks are translucent, leading to a translucency of 32% at positions where segments are printed. Note that the display is fully transparent at locations without segments. Fig. 8b shows an application example for a shop window showcase.

Integration with Static Visual Print

A display can be printed alongside and integrated with static visual print. The designer uses an office laser or inkjet printer to print static visuals onto the paper or PET substrate. Next, display primitives are printed with screen printing onto the same substrate. This enables the following functionality:

Adjacent: Display primitives can be adjacent to printed visuals, for instance allowing for underlines or pop-out elements that light up on demand.

Contour: They can be more directly integrated. For instance, a static printed headline can be augmented by a luminescent contour. As long as the segment is not filled, visual print inside the segment remains fully visible.

Highlight: If the display primitive is printed at the reverse side of a slightly translucent substrate (see Fig. 3b), it can glow though static print on the front side and act as a dynamic highlight. The example in Fig. 8c demonstrates a highlight printed on the reverse side of office paper.

Integration with Printed Electronics

PrintScreen enables integrating display primitives with additional printed electronic applications on a single substrate. The bottom electrode layer can be used for designing additional electronics next to display primitives. Using silver ink for the bottom electrode, users can design printed traces and components. The principles for silver-ink printed components from previous work directly transfer to this case, e.g. for printing sensors [7, 9, 13]. Moreover, additional surface-mount components can be soldered onto the substrate.

DISPLAY SHAPES

PrintScreen offers the designer a high degree of design flexibility, supporting custom 2D and 3D shapes as well as reshapeable displays.

2D Shapes

Virtually any (rectangular, circular, irregular) 2D contour of the display can be realized in the digital design and then cut out of the fabricated display substrate. The only restriction is that each segment must be connected with the controller. The size of a display can range from only a few square centimeters up to large sizes. Screen printing of up to A2 size is feasible with hobbyist's toolkits.

3D Shapes

Screen printing does not allow for printing on curved objects. However, it supports printing on flexible substrates. Once printed the substrate can be deformed to create curved or folded 3D surfaces (see the examples in Fig. 1 and Fig. 10.

Shape adaptable

The flexibility of the substrate even allows for resizable and deformable displays. In technical experiments, we could demonstrate that the printed display can be folded anywhere on its surface and remains fully functional. It can also be rolled up on a scroll with a radius of 3 mm; this enables for applications for rollout displays. A technical evaluation shows that the displays are very robust to repeated bending or folding.

INTEGRATED SENSING OF USER INPUT

Sensing of user input is a key requirement for interactive display surfaces. We contribute an approach for integrating different modalities of input sensing with a printed TFEL display, using the same set of electrodes both for display and for sensing. It is *not* necessary to print additional sensing elements on top or behind the display, as it would be necessary for LCD screens. We demonstrate the principle with capacitive touch sensing.

The approach is based on the key insight that the phosphor layer only lights up when a high AC voltage is applied on one electrode while the electrode on the other layer is grounded. It does not light up when DC or a low voltage AC (we identified < 14 V) is applied, or when one electrode is set to high impedance. Many sensing approaches fulfill these requirements, e.g. for sensing of touch [6, 7, 26], hover [7] or deformation [7], to give only a few examples.

By time-multiplexing between a display and a sensing cycle, the electrodes on one, or even on both layers, can be used for sensing. In case of DC sensing, the driver IC is turned off during the sensing cycle. The time for discharging depends on the charge of the internal capacitors. In our implementation, we measured a maximum discharging time of 1.7ms.

As an example instantiation, we implemented capacitive touch sensing using projected capacitance [26]. During the sensing cycle, we leave the high voltage AC signal on the lower electrode, set the higher electrode to high impedance and measure the transmitted signal. When touching the electrode, the signal amplitude drops (see Fig. 9). The amplitude of the signal is used for recognizing touch contact, as introduced in [26].

If display and sensing cycles alternate quickly and the display cycle is sufficiently long, there is no perceivable decrease in display quality. We identified the following cycle durations to not add flickering: a display cycle of 5ms is followed by a sensing cycle of 2ms. This results in a frame rate of 140 Hz. The sensing cycle decreases the luminance of the display by 24%, which however can be fully compensated for by increasing the AC voltage. If used in a passive matrix display, the frame rate is divided by the number of lines of the display.

The spatial resolution of sensing depends on the number, size and arrangement of display electrodes. If required, additional electrodes used exclusively for purposes of sensing can be printed in-between display segments. It is also possible to enlarge the top and lower electrodes of a display segment for sensing, without increasing the segment on the phosphor layer.

APPLICATION EXAMPLES

We present five application examples of custom-printed displays. They instantiate various dimensions of the design space and demonstrate the potential for applications in ubiquitous, mobile and wearable computing. The applications are illustrated in Fig. 10

Interactive Paper Postcard

Interactive display segments can be integrated with static visual print. We printed a paper postcard that features on-demand visual information on a historical car. Two printed touch areas capture user input. The display segments are printed on the reverse side of the postcard. This application shows the high resolution of very custom-shaped segments and demonstrates the applicability for augmented paper and smart signage applications.

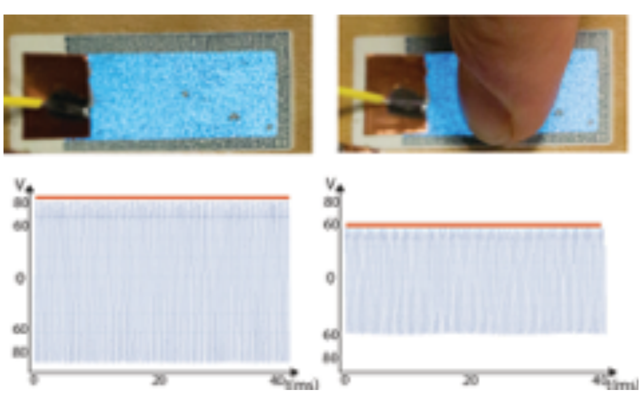

Figure 9. Touch sensing. The amplitude of the AC signal drops when the segment is touched.

Figure 10. Application examples

Interactive Watchstrap

PrintScreen enables customized wearable displays. In this application, a notification display is integrated in a watchstrap of a traditional wristwatch. It is printed on the backside of a thin white PET film, which is laminated onto the watchstrap. The display can be customized to fit the individual shape of the watchstrap. This smartwatch concept has the benefit to maintain the esthetics of a traditional watch.

Printed Pong

To demonstrate interaction with a printed matrix display and its responsiveness, we implemented an instantiation of the Pong game. The 16x16 matrix display features two capacitive touch buttons to control the paddle. Technical Evaluation.

Awareness Flower

We augmented an artificial plant with displays on the backside of its flexible leafs, to provide awareness information. If an update (e.g. a new e-mail) arrives, the segment lights up. This application demonstrates how PrintScreen enables ubiquitous displays that seamlessly integrate with the underlying object and fade into the background when not needed.

Integration with Electronics

This application demonstrates that PrintScreen can be used for creating flexible circuit boards with integrated display elements. The bottom electrode layer contains additional printed circuitry for wiring of additional electronic components. A physical bend sensor allows the user to modify the number on a seven-segment display.

TECHNICAL EVALUATION

Luminance

The light intensity of the display can be controlled by varying the AC voltage (amplitude and frequency). We analyzed the maximum light intensity of the displays. It depends on several factors: the substrate, the AC voltage and the strength of the inverter. When driven with the DC12V10M inverter at its maximum input voltage of 12V DC, the luminance of the display varies between 120 and 280 cd/m^2. On paper, PET, ceramics and leather, we measured a maximum luminance of approx. 170 cd/m^2. On very smooth materials (steel and marble), 280 and 250 cd/m^2 are reached. On wood, a quite porous material, we measured only 120 cd/m^2. In our experience, the strength of the inverter is the main limiting factor. In experiments with a stronger inverter, we measured intensities between 270 and 570 cd/m^2 at 18V DC. When using the mobile driver IC chip [28] with 7V DC, the displays are less bright, ranging between 15 and 35 cd/m^2. This is comparable to a super bright white LED.

Bending and Folding

To analyze how robust the display is when repeatedly bent or folded, we used an automated test setup. We used a display sample with a 6x1.5cm single segment, printed on office paper. A simple robotic apparatus bent or folded the display repeatedly, returning each time to a completely flattened state. A light sensor, placed 10 cm above the display surface when in flat state, automatically measured the luminosity after each deformation.

In a first test, the apparatus bent the display successively 10,000 times to a radius of 1.5 cm. After the test, the display was still functional and did not show any decrease in luminance. We tested this high number of repetitions to account for continuous deformations occurring when the display is used in wearable applications.

In a second test, the apparatus fully folded (with a sharp folding crease) and unfolded a different display sample a total of 3,411 times before parts of the segment ceased to emit light. During the test, the display did not show any decrease in luminance.

DISCUSSION AND LIMITATIONS

Ease of Fabrication

All display samples presented in this paper were printed by two persons who both were not familiar with screen printing before joining this project. They used online tutorials and videos on the Web to learn the process. It took them between 3 to 5 hours to get familiar with the theory and another day to get practical experience. They did not encounter any real difficulties. One of the persons first had problems with homogeneously applying the UV-sensitive emulsion onto the mesh for UV lithography, but had learned doing it correctly after a few trials. Fine prints with thin lines require a steady hand. Despite the imprecision of the manual process, our non-experts could robustly print conductive lines and lighting dots of 300 μm width and diameter. Printing of the displays for our example applications took between 2 and 4 hours. This demonstrates the practical feasibility of the approach.

Display Color

Our process requires for each segment or pixel to choose the color at design time. For our display samples, we used only one color. A full color display could be realized by printing three red, green and blue sub-pixels for each pixel [15]. Given the maximum pixel density in manual print, this is a viable approach only for displays that are looked at from some distance.

Safety

All substances used for fabrication of the displays are non-toxic.

Safety for production: Users should read the health and safety guidelines in the material data sheets of the inks. It is recommended that the printing process take place in a well-aired room especially when curing the inks. Users should wear rubber gloves and goggles to protect eyes and hands. The display should be sealed properly.

Safety after production: After the inks are cured, the display is safe to interact with. A current of max. 10mA is considered being physiologically safe [31]. For example, the EL driver IC can provide a maximum output current of 1.0 mA at 220 Vpp [28]. This driver IC can drive a segment area of 4 sq. inches. If we assume 10 driver ICs are connected in a parallel circuit (driving a surface of 40 sq. inch, a reasonable size for most mobile/wearable applications) the overall current is max. 10mA.. If stronger inverters are used or if the display is exposed to mechanical stress or scratching, we recommend lamination with an insulating film.

Comparison with OLED Displays and Electronic Paper

In applications where a high-resolution matrix display or use of a full-color display is a prime requirement, off-the-shelf OLED or electrophoretic displays are still the solution of choice. However, if very strong bendability or even foldability is required for functional interface prototypes, our approach is without competitors, as to our knowledge such displays are neither commercially available nor can they be produced using a different approach. Likewise, PrintScreen is to our knowledge the only solution for designers, makers and HCI experts that allows direct integration of displays with various base substrates, very thin dual-sided and translucent displays and custom shapes.

CONCLUSION

PrintScreen is an enabling technology for digital fabrication of customized thin-film displays. We presented a systematic overview of graphical display primitives that act as buildings blocks for the digital design of the display. In order to instantiate the design, PrintScreen contributes two methods for rapid and inexpensive fabrication of the display, in a lab environment, print shop or even at home. The displays are deformable (even fully foldable and rollable) and can be highly customized by the user in several dimensions: their 2D and 3D shape, the material they are printed on, and the way contents are displayed. We further presented a framework that integrates sensing of user input (e.g., touch input) right into the display. Due to its versatility, PrintScreen opens up a wide space of new applications in ubiquitous, mobile and wearable computing.

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Eidesstattliche Erklärung

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