Integration of Screen-Printed Electroluminescent Matrix Displays in Smart Textile Items – Implementation and Evaluation

Artem Ivanov, Maximilian Wurzer
Faculty of Electrical and Industrial Engineering
Landshut University of Applied Sciences
Landshut, Germany
Artem.Ivanov@haw-landshut.de

***Abstract*—Present work describes integration of electroluminescent matrix displays in textile objects and evaluation of possible practical applications. Aspects restricting the application of electroluminescent elements in clothing, like high driving voltage and low light intensity, are discussed. Possible solutions for these issues are proposed. A low-cost driver for a passive matrix display and the underlying non-conventional method of multiplexing is presented. Measures to bring the driver circuit to the conformity with safety regulations are described. Obtained results show that the integration of electroluminescent pixel displays into textile items can be carried out with low technical effort using available technology; a good visibility is achieved in most indoor situations.**

Keywords—electroluminescence; electroluminescent display; printed display; passive matrix; smart textiles; printed electronics.

I. Introduction

Electroluminescence (EL) denotes light emission of a phosphor substance in electrical field. This effect is used for example in backlights of mobile devices, where it accounts for homogeneous illumination [1], or for safety lighting in interior design [2]. Another prominent application is thin film electroluminescent displays (TFEL) as a choice for extreme conditions [3]. Currently the first textile products with electroluminescent elements enter the market: a jacket by Helly Hansen with integrated EL elements for better visibility in darkness has won the ISPO Award 2017/2018 [4].

Since the structures required for EL elements are easy to produce using screen printing, and a number of polymer based paste systems is available on the market, electroluminescence is often discussed as an important technology for flexible printed electronics. Currently the majority of the products and prototypes incorporating printed EL elements rely on single light emitting areas or pre-defined pictograms in their use cases. The present work enhances the scope of applications to pixel displays. It is devoted to the implementation of printed electroluminescent displays (ELD) with a passive matrix, the necessary driver electronics and the aspects of integration of ELDs into smart textile items.

There are several aspects restricting the application of electroluminescent elements in clothing applications. First of all, the brightness of available phosphor materials is currently relatively low. Furthermore, high voltage requirements for driving signals bring safety concerns and difficulties in electronics design.

Our work addresses these critical aspects evaluating integration of ELDs in textile objects. The results show that reasonable applications can be designed even with the current state of technology.

II. Principles of Electroluminescence

A typical EL stack resembles a planar capacitor and consists of two electrode layers, an active phosphor layer and an insulation layer and can be constructed as shown in Fig. 1. At least one of the electrodes is transparent to let the light out (bottom electrode in Fig. 1). An AC voltage in the range of 100 V induces an alternating electric field between the electrodes that makes the charge carriers in phosphor material move and generate light. The necessity of alternating driving voltage is given by the capacitor-like construction of the stack – an applied DC voltage would lead only to a short light flash during the charging of the capacitor.

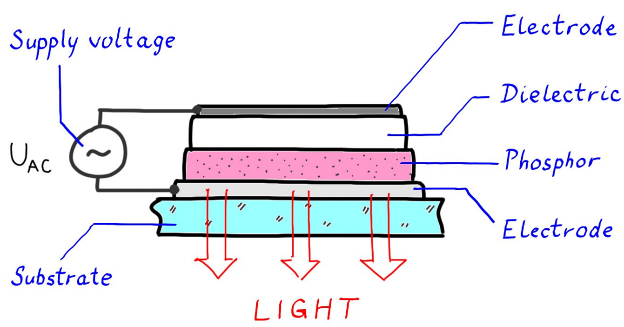

Fig. 1. Typical stack structure for printed electroluminescent elements. Typical thickness of the single layers amounts to 10 µm to 50 µm for screen printed structures. Usual values of driving AC voltage lie higher than 100 V.

This type of structure can be easily enhanced to represent a pixel display with a passive matrix: bottom electrode is segmented into several line electrodes and the top electrode – into column electrodes (or vice versa). Each of the line and column electrodes is separately driven according to the pattern to be displayed.

Driving such structure is, however, challenging – because of the capacitive coupling of lines and columns, spurious lighted pixels appear along the chosen line and column electrodes [5]. The ways to drive the passive matrix of thin film electroluminescent displays were subject of patents since the 1980s, e.g. [6], [7] and [8]. In this approach several square wave and pulsed voltages are required: the "write" voltage ($U_w \approx -160$ V), the "modulation" voltage ($U_m \approx +50$ V), the "refresh" voltage ($U_r \approx +190$ V) [7]. The driver circuits must allow high slew rates and have to be implemented for all lines and columns. This method allows high quality images on thin film EL displays but is difficult to transfer to applications of printed electronics: one reason is, a higher layer thickness requires higher driving voltages and, additionally, the price segment addressed by the printed electronics does not allow high driver costs.

Successes in driving printed electroluminescent passive-matrix displays were reported in the literature a decade ago [9]. Nonetheless, such displays are still not available on the market. The main problem lies presumably in the difficulty to design a miniature low-cost driver electronics. On one hand, integrated circuits with suitable properties do not exist. On the other, the proposed method is relatively complex in its software implementation, making it problematic to use simple microcontrollers in the driver.

A way to overcome these difficulties and to allow driving of passive-matrix ELDs using compact and cheap electronic circuits using readily available electronic components was proposed in [10]. This method relies on an unconventional approach to drive electroluminescent structures and is simple in implementation. The first generation of ELD demonstrators allow already a reasonable image quality, though is limited in achievable contrast. Work is ongoing to substantially increase the contrast capability of the driver-display combination.

The principle of driving the display is illustrated in Fig. 2. Here an example is shown, where only two pixels are lit; their coordinates are given by L1/C1 (Line 1/Column 1) and L2/C2 (Line 2/Column 2). All line and column electrodes are driven with square wave voltages, which alternate between $U_{low} = 0$ V and $U_{high} \approx 150$ V; no other voltage levels are required. To make a pixel glow, its column voltage is inverted in respect to the line voltage: on the crossover of the given line and column an AC voltage with amplitude U_{high} is produced. A pixel will remain dark, if the line and the column voltage alternate in phase to each other or if one of these voltages (e.g. line voltage) has a constant value, as illustrated by the pixel L1/C2 in Fig. 2. The emission of light can be treated as consisting of single flashes occurring every time when the display capacitance is charged or discharged. In an active pixel more flashes are produced than in a dark pixel; the ratio between these numbers gives the contrast of the display.

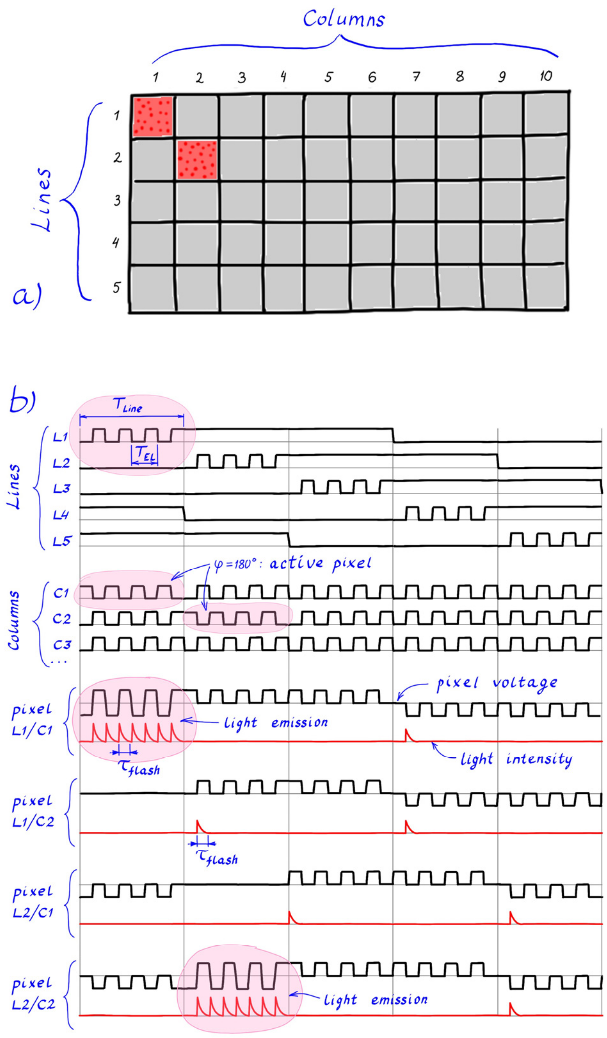

Fig. 2. An examplary state of the display with two active pixels (a) and the corresponding signal wave forms (b) to make the pixels L1/C1 and L2/C2 emit light (after [10]). The driving frequency $f_{EL} = 1/T_{EL} \approx 1$kHz, the duration of one display frame $T_{frame} = 5 \cdot T_{line} \approx 30$ ms.

The logical signals are generated in a microcontroller and are transmitted using a serial bus to a high voltage driver IC. Fig. 4 and Fig. 5 below show the photograph and the principle circuit diagram of the driver electronics.

III. Motivation

The main goal of the present work was to evaluate from the technical point of view, whether electroluminescent displays can be reasonably used in clothing. There are two principal concerns that stand in the way of developing wearable applications with printed electroluminescent displays: intrinsic low intensity of the emitted light and the need of a high supply voltage with a potential impact on safety. The importance and the technical solutions concerning both issues can be evaluated using the available state of the art. This allows to see the success chances of the exemplary applications on an early stage.

Another direction of investigations was an assessment of reasonable applications, which are possible with the current state

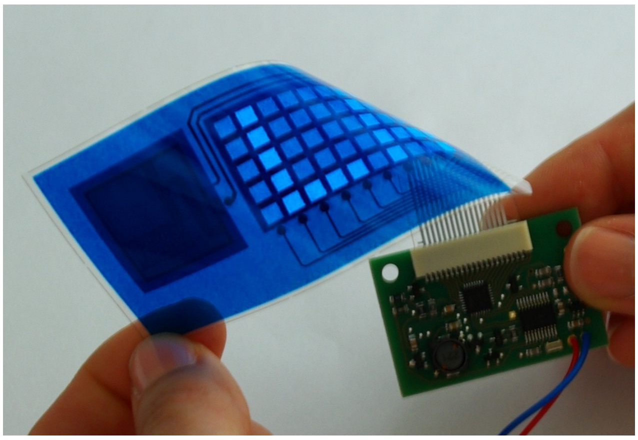

Fig. 3. Display-driver system used for integration into textile objects.

of the technology for the printed ELDs. Most of these aspects were treated in a bachelor thesis at the Landshut University of applied sciences [11].

IV. Practical Realisation

The driver electronics from [10] was adapted and optimised to drive printed electroluminescent displays integrated in clothing. Displays with the size of 10 by 5 pixels and a logo field were screen printed on PET (polyethylene terephthalate) foils; pixel size amounted to 3 mm by 3 mm. The photographs of the EL display and of the driver electronics are shown in Fig. 3 and Fig. 4.

The use case under consideration is application of printed electroluminescent displays in textile items like clothing and bags. The integrated display must have a high degree of mechanical flexibility to adopt its form to the momentary form of the "host" textile object and to not disturb the person who wears it. Possible solutions are

- integration of a display printed on a separate flexible substrate, e.g. on a plastic foil, into a textile object or
- printing display structures directly on the fabric, which could bring a superior mechanical flexibility.

In the first case either an additional plastic foil or an additionally printed dielectric layer can be used for electric insulation; in the second case printed dielectric should be used to not deteriorate achieved better flexibility of the display. The required mechanical properties imply in both cases a very thin resultant display construction and so make a stable electrical insulation difficult.

The consequence for a real-world textile object with a display would be an insulation with a relatively low long term mechanical stability. This means, the minimum requirement on the driver circuit is to limit the current to the display to a not dangerous value. In this case even touching a damaged display with broken insulation would be safe. Safety regulations define following criteria for an AC voltage which does not need insulation [12]:

- the voltage is below 25 V or

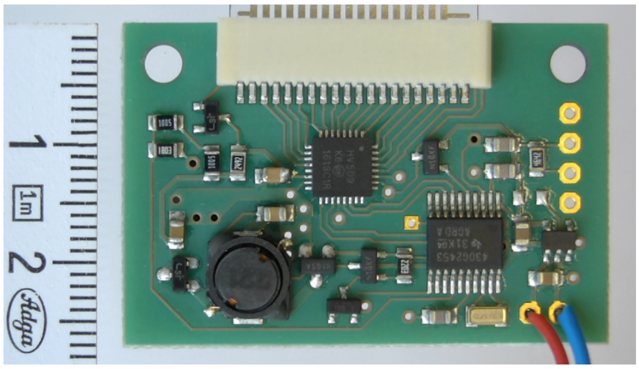

Fig. 4. Driver electronics for the printed electroluminescent display.

- the possible short circuit current of the supply is below 3 mA or
- the available electric energy is below 350 mJ.

If at least one of these criteria is satisfied, no electrical hazard is said to exist.

The technical specification 60479-1 of International Electrotechnical Commission (IEC) [13] defines four major current ranges according to the effect on a human. In the ranges AC-1 and AC-2 no hazardous physiological effects take place. To stay within the AC-2 range the long term current flowing in the body must be limited by 5 mA.

In out tests the electroluminescent displays were printed on PET foils and not directly on fabric to hold technological difficulties in the printing process itself at a low level. Driver electronic was assembled on a FR-4 based PCB and was connected to the display via an FPC connector (flexible printed circuits). The safety features were implemented on the PCB.

To have a minimalistic solution, the driver circuit is logically divided in two parts with "safe" and "not safe" voltage. The output multiplexer IC gets its high voltage supply via a series resistor R_S and belongs to the safe part of the circuit (Fig 5). Signals to the lines and columns of the display are then limited in their current capability by the only resistor R_S. The driver PCB can be easily electrically insulated using a flat plastic case; only the display itself can come in contact with the user. The unsafe part of the circuit (high voltage generation) can be

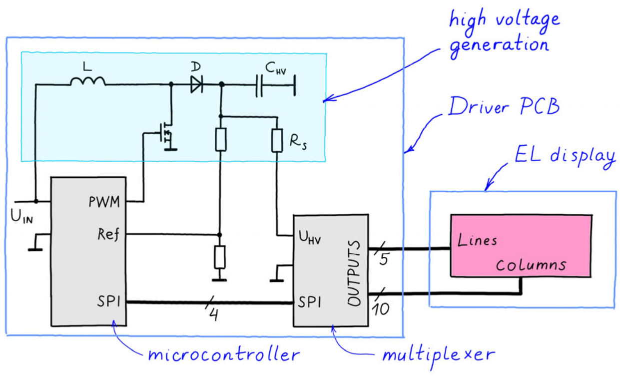

Fig. 5. Principle circuit diagram of the display–driver system showing physical boundaries of components. The portion "high voltage generation" must be electricaly insulated for safety.

additionally encapsulated, e.g. using globe top compounds; in this case it would be possible to omit the plastic case of the PCB in some applications.

To achieve the best readability of the display in tested application, optimisation of several parameters was performed: the value of generated high voltage, the frequency of driving AC voltage, the frame frequency for the display and the series resistance. The goal of optimisation was to fit together two concurrent requirements:

- to achieve high brightness of the display, i.e. the driving voltage should be high enough with a high output current capability, and
- to ensure the user safety in case of breakage of display insulation, i.e. the maximum current must be below the limit given by the regulations.

The optimisation was carried out starting with the highest voltage and output current, which the electronic components allowed, and consequently restricting the maximum output current to be below the safe limit with a sufficient margin. Later comparison of the initial and the "safe" state of the system was carried out. It showed a perceptible decrease in display intensity, confirming the importance of considering the regulations before any evaluation of suitability of the display system for a given application is performed. After optimisation of the driver, textile items with integrated displays were evaluated to determine which reasonable applications could be possible with obtained properties.

For the assessment of electrical safety of the system, the worst case was treated. It implies that the display insulation is broken, and the user simultaneously touches two conductors carrying opposite polarities. This situation results in the maximum current, which the driver is able to source into the user's body.

According to the technical specification [13] the total impedance of the body to electric current Z_t can be represented by the internal tissue impedance Z_i in series with the impedance of the skin Z_s (to model the input and the output contact for the current flow Z_s is taken twice):

$$Z_t = Z_s + Z_i + Z_s.$$

The skin impedance can be represented by a capacitor connected in parallel to a resistance, the internal tissue impedance can be treated as a pure ohmic resistor of the order of magnitude of 100 Ohm or below. The impedance of the skin depends on several factors, some of them with the corresponding effects are:

- skin impedance decreases if the area of electric contact rises or the contact pressure rises or the skin is getting wet,
- at a higher frequency of the flowing AC current (>5 kHz) capacitive part of the impedance leads to an effective short circuit of the skin impedance,
- under action of voltages higher than approximately 100 V electric breakdown of skin can happen also bringing its impedance almost to zero.

If the ELD driver electronic is touched by the user, at least the second and the third factor can easily result in the short circuiting the skin impedance. That is why in the worst case treatment the total body impedance can be regarded to be equal to the internal impedance of the body: $Z_t \approx Z_i$. This fact was taken into account in design of the safety features of the electronics.

V. Results and Discussion

Measurements were performed with ohmic load resistances to model the total body impedance in different touch scenarios. The resistors were connected to the driving voltages of opposite polarity and were varied in their values. The voltage drop on the resistor was monitored and the effective value of the flowing current was calculated. The experiments were carried out with several values of serial safety resistors R_s in the driver electronics to find the optimal value. Basing on the obtained results the maximum output current was set to 4 mA, which is 20% lower than the 5 mA limit for the AC-2 range of the regulation DIN IEC/TS 60479-1 [13]. The output current dependence on load resistor value for the optimal value of R_s is given in Fig. 6.

A slightly higher value of the serial resistor R_s can be used to restrict the output current to under 3 mA. In this case the electronics would even become a voltage source that does not need insulation [12], but the display intensity will be further reduced. For our tests of display readability this measure was not implemented.

In our experiments displays built with paste systems of two manufacturers (DuPont and Gwent) were tested. Most attention was payed to testing different phosphor materials and transparent conductors. Colour of emitted light, nominal brightness, life time and printing properties were considered, the goal was to optimise the performance of the entire display.

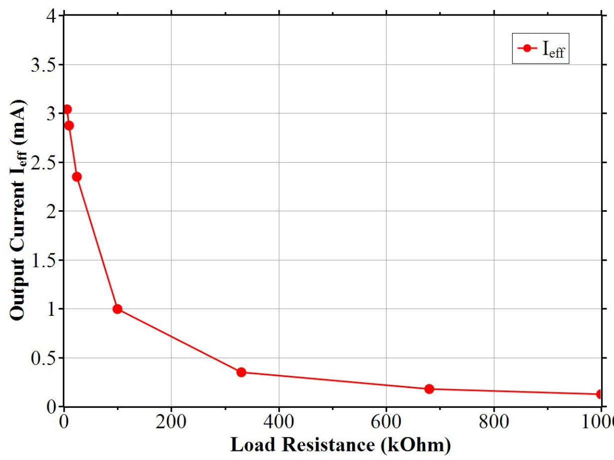

Fig. 6. Electric current in the load resistor which models different touch scenarios of the electroluminescent display. The driver output current lies below 4 mA for all values of load resistor.

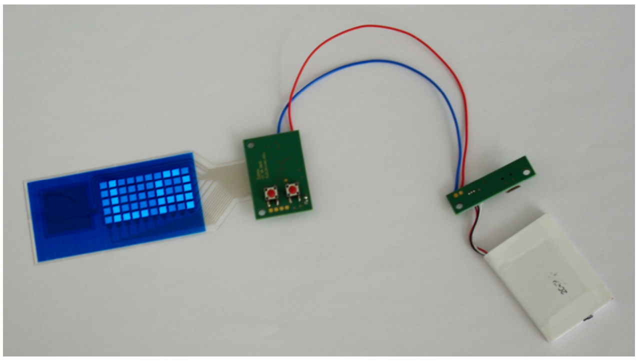

Fig. 7. Complete system for the integration in textile items: printed electroluminescent display, driver PCB, Li-Ion rechargeable battery with charging circuit.

Best results were achieved with phosphor pastes emitting blue and green light. Within this group of materials very similar light intensities were measured at similar levels of electric power consumption. The similarity in the performance can be explained by the current limiting: a brighter display requires a higher driving current resulting in a higher voltage drop on the safety series resistor. Since no substantial differences in the performance of the display with the tested paste systems are observed, the choice of the paste system for similar projects can be done basing on behaviour of the pastes during screen printing process and the ease of handling.

As a means to improve the contrast of printed displays optical colour filters were investigated. Blue transparent inks were printed on the display substrate (on the light emitting side of the display). Tests in different illumination conditions confirmed a positive effect of the filter on display contrast at higher levels of ambient light intensity. In low light conditions displays without filter demonstrated higher intensity at a similar contrast.

Several textile objects with integrated electroluminescent displays were designed to support the evaluation: test were carried out with T-shirts, caps and bags. The system (Fig. 7) consisting of a printed display, a driver PCB, a Li-Ion rechargeable battery and its charging circuit with a mini USB connector was fitted into test objects using fabric pouches, Velcro fasteners or direct sewing. The challenge of the integration is not only to favourably place the display but also to mount the battery and the driver electronics in a non-disturbing manner. Examples of integration are shown in Fig. 8; results can be summed up as follows:

- Objects like bags, backpacks, heavy jackets, caps or hats suit best for the integration. They offer enough room for electronics and battery, so that it is concealed from the external eye and also does not compromise the wearing comfort of the user.
- Another advantage of these objects is a relaxed requirement on frequently washing. It allows to use electronics without complicated sealing – in a seldom case of washing the electronic system would be dismantled.

Fig. 8. Examples of textile objects with integrated ELDs: a back pack and caps of two types. Displays with and without optical filters are shown (lighting up in blue and in blue-green respectively).

- T-shirts and similar items proved to be not suitable for the intended integration. The reason lies in the stretchable fabric usually used for them. One point is, mechanical properties of displays printed on plastic foils do not allow to make their mounting indiscernible. Another issue is connected with a not negligible weight of the battery and electronics – it influences the natural shape of the fabric, reveals it to an external observer and discomforts the user.
- We suggest using an ELD with a higher amount of pixels in horizontal direction in the future. The main reason is a better perceived readability: texts are easier to read if words can be displayed in their full length. The ongoing work is focused on demonstrators of printed electroluminescent displays with a two and three times higher number of pixels in horizontal direction.

The readability of the displays was evaluated by several test persons in situations with different illumination conditions. The results of the tests are presented in Table I together with the illuminance recorded in the given situation (here for a display with an optical filter). It is seen that for the most of indoor situations sufficient readability is achieved. Applications outdoors can also make sense, if they are intended for use during darker periods of time: morning, evening or night hours. For example, a better visibility of persons in darkness can be achieved, if they wear electroluminescent displays integrated in the clothing or bags.

TABLE I. READABILITY OF ELECTROLUMINECSENT DISPLAYS UNDER DIFFERENT ILLUMINATION CONDITIONS.

Experimental location	**Illuminance (lx)**	**Readability of ELD**
Dark cellar	0.1	Very good
Unlit corridor	25	Very good
Darkened room	85	Very good
Room with indirect sunlight	215	Good
Brightly lit room	710	Good
Sunlit glass passage	980	Mediocre
Outdoors at light haze	5700	Poor
Outdoors in indirect sunlight	30000	Bad
Direct sunlight outdoors	98500	Bad

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Landshut University of Applied Sciences in conducting this research project and to express special thanks to the technical staff of the laboratory for hybrid electronics of UAS Landshut, especially to Mr Sattelberger and Ms Bichlmeier, for their help in preparation of samples and carrying out experiments.

REFERENCES

[1] Timex Expedition Base Shock Watch, Product page. [Online]. Available at: http://global.timex.com/node/102071.

[2] EL-Technik, “Applications – Safety lighting.” [Online]. Available at: http://el-technik.de/Leuchtfolie/Safety-lighting.html.

[3] Beneq Oy, “Technology – Thin Film Electroluminescent Displays.” [Online]. Available at: http://beneq.com/en/displays/technology.

[4] Light Flex, “Winner of the ISPO Award in the Outdoor Segment 2017/2018.” [Online]. Available at: http://lightflextechnology.com/winner-ispo-award-outdoor-segment-2017-2018/.

[5] S. Olberding, M. Wessely, J. Steimle, “PrintScreen: Fabricating Highly Customizable Thin-film Touch-Displays,” Proc. 27th annual ACM symposium on user interface software and technology, pp. 281-290, 2014.

[6] W. Barrow, L. Blacken, B. Dolinar, R. Flegal, P. Gulick and C. King, “Staggered refresh pulse generator for a TFEL panel,” United States Patent 4691144, 1987.

[7] B. Dolinar, R. Flegal and L. Lewis, “Energy-efficient split-electrode TFEL panel,” United States Patent 4739320, 1988.

[8] W. Pietro, S. Fielder, “Method ans apparatus for driving an electroluminescent display,” United States Patent 8810555, 2014.

[9] D. Johnston, C. Barnardo, C. Fryer, “Passive multiplexing of printed electroluminescent displays,” J. Soc. Inf. Disp., vol. 13/6, pp. 487-491, 2005.

[10] A. Ivanov, “Vereinfachte Ansteuerung gedruckter Elektrolumineszenz-Displays mit passiver Matrix,” Proc. Symp. MST, Landshut, pp. 72-83, 2016.

[11] M. Wurzer, “Machbarkeitsstudie zu Smart Textiles Anwendungen mit Elektrolumineszenz-Displays,” B.S. Thesis, UAS Landshut, Landshut, 2017.

[12] Deutsche Gesetzliche Unfallversicherung (DGUV), “Sicher experimentieren mit elektrischen Energie in Schulen,” Information brochure BG/GUV-SI 8040, p. 27, September 2012.

[13] International Electrotechnical Commission (IEC), “Effects of current on human beings and livestock - Part 1: General aspects,” Technical Specification DIN IEC/TS 60479-1:2007-05, October 2006.