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Luminous Matter Electroluminescent Paper as an Active Material

Abstract

Materials play a vital role in tangible interaction design. However, the materials are often used passively, as elements to be actuated by ready-made electronic components rather than inherently active parts of an interactive system in their own right. In this paper, we challenge that approach through a series of material experiments involving electroluminescent paper. The results are different types of self-illuminating paper which exhibit peculiar responsive behaviours while maintaining the affordances and ephemeral qualities of conventional paper. We demonstrate a number of techniques for expressive design through hand painting, folding and using water as an activator and distributor of light. We show how direct engagement with inherent active qualities of materials leads to novel creation processes and design ideas.

Keywords

Active Materials, Electroluminescent Paper, Ephemeral Interfaces, Smart Materials

1. Introduction

For more than ten years, physical computing has dramatically changed the way in which we use digital technologies in design and architecture. Today, interactive objects are a collage of interconnected sensors and actuators that can electromechanically move, emit light or sounds. Designers can easily prototype using tools such as Arduino combined with these various hardware components. Such electronic components are often combined with traditional materials such as wood or metal for their durability, flexibility or tactile qualities. Those materials can be activated by motors or other types of actuators. They do not move or actuate by themselves - they are being acted upon.

There is a range of materials, however, whose inherent properties allow them to act and respond to certain environmental conditions or specific stimuli such as electricity, vibration, pressure or light. Such materials are often not commercially available or the processes of creating them are too complex to be brought to a design studio or teaching environment. In order to address this issue, we need to develop processes, methods and tools that can allow designers, artists and architects to create novel materials and to work with their inherent responsive properties. A new kinds of aesthetic experiences may be enabled when classical physical computing is extended to material experimentation on the threshold between the mechanic, chemical and electronic.

2. Background

2.1. Active Materials

In the context of interaction design, some projects have utilised the inherent properties of materials to sense different stimuli such as sound or temperature, or to actuate with movement, sound or vibration [1]. One interesting example comes from a musical interface design where conductive inks and various substrate materials were used to create paper sensors that can detect position, pressure and bending [2]. However, many projects are based on off-the-shelf actuators that move passive surface elements such as metal, for example in *Aegis Hyposurface* [3]. A more promising example is the use of pneumatic actuators as a part of the architectural structure itself, like the *Muscle Body* project by Hyperbody research group at TU Delft [4]. Other approaches use weaving of commercially available materials such as optical fibres into fabric, as in *Energy Curtain* [5]. Rare examples of using inherent properties of materials include the use of wood, which can deform in response to varying humidity [6] and the use of bimetals which change shape according to variations of temperature [7]. The active properties of novel materials themselves appear to be hard to work with, reflected by the lack of examples that exploit them in design fields.

However, material sciences are increasingly developing so-called smart materials that can respond to stimuli and environmental changes in a controlled way. Many such materials are engineered on a molecular scale and thus can only be fabricated in a laboratory. Dealing with materials on a nano scale not only requires specialised facilities, but also removes the creator from the direct sensing and handling of the material. Tacit knowledge of materials plays an essential role in design and arts, as such intimate relationship with a novel material enables a designer or artist to explore its aesthetic potential. Artworks resulting from the *Liquid Things* research project are an interesting example of aesthetic outcomes that a long-term engagement with novel materials may lead to [8]. The project's practical research is grounded on theoretical discourse examining the coupling of material, process and imagination [9].

The authors of the *Transitive Materials* approach argue that working with novel materials requires an embodied understanding similar to those found in craft practices [10]. This enables the designer to develop material composites which may function as frame, skeleton, sensor, actuator and/or processor. Examples from the authors make use of smart materials combined with traditional ones and electronic hardware for various functional and aesthetic goals. For example, in so called *Pulp-based Computing* where electronic components, conductive inks, shape-memory alloy and LEDs were integrated into the paper during the papermaking process. Their loud-speaker example combines a sensor and actuator, as a screen-printed spiral of conductive ink both reacts to touch and emits sound [11]. The idea of *Transitive Materials* is to seamlessly couple input, output, processing, communication, power distribution and storage. However, an example which accomplishes all these goals through smart materials is yet to be seen.

A more recent conceptual framework for so-called *Becoming Materials* focuses on temporal and responsive aspects of novel computational materials [12]. Their prototypes are an example of a classical physical computing approach with sensors and actuators added to conventional materials. In *PLANKS* a hardware microphone was added to plywood boards which were then moved by motors when activated by sound [13], while in the *Telltale* project air pressure is used to inflate and deflate furniture in order to communicate household energy consumption. However, the *Becoming Materials* approach points to the importance of temporal aspects in materials and explores their relationship to context and use.

In this paper, we introduce the term *Active Materials*, as a working concept to describe our approach that engages with inherently active properties of materials and sets to uncover aesthetic potential hidden in the material. *Active Materials* are inherently capable of changing their states and/or properties when exposed to specific stimuli such as light, temperature or electrical charge. For example, electroactive polymers (EAPs) stretched into thin foils attached to flexible frames can change their shapes under an electrical field, as shown in *ShapeShift* [14]. Although EAPs were originally developed for robotic applications and haptic interfaces, in *ShapeShift* they were modified to explore their aesthetic potential in an architectural context. Similarly, our goal is to approach such novel materials in a way that enables a larger spectrum of aesthetic expression. Conceptually, it is grounded in a material turn in humanities, more specifically theories that see materials as a part of a continuous flow of matter in the environment. This conceptual framework requires a new understanding of creative practices in design, arts and architecture [15], as well as new techniques of approaching *Active Materials* in a more embodied and tacit way. Only in this way can we explore their aesthetic qualities and shift focus from performance and durability typical of an engineering approach to qualities such as ephemerality and aliveness.

2.2 Ephemerality in Paper Interfaces

The material explored in this paper, namely electroluminescent (EL) paper, challenges us with issues of longevity and durability. The fragile qualities of the EL paper we created are in direct opposition to what we expect from the converging areas of consumer electronics, digital technology and architectural environments. They also appear to contradict findings from *Sustainable Interaction Design* which emphasises designing for long lasting utility not for the transient [16]. The rapid fabrication and obsolescence of electronic devices clearly leads to waste and resource issues, so by extending utility we can somewhat alleviate these environmental consequences. However, longevity poses its own problems, as the materials that lend to a greater sense of durability and therefore supposed emotional attachment to electronic devices [17], are also the materials that will persist for decades or potentially millennia after the device becomes obsolete. As we increasingly apply electronics to artefacts and environments, following the ambient computing paradigm, this issue will become an ever pressing consideration. The emerging field of *transient electronics* may offer a solution through electronic devices that are designed to dissolve or biodegrade over a predefined time frame [18].

Electronics that can biodegrade similar to paper have an interconnectivity with the environment, ourselves and other agents, potentially opening up new insights and novel forms of interaction. Döring, Sylvester and Schmidt proposed *Ephemeral User Interfaces* “as having at least one UI element that is intentionally created to last for a limited time only” [19]. They point out that experiencing something fleeting and transient has a special resonance with people, and by incorporating such qualities into interaction design practices new avenues for interactive devices can emerge. Certain material choices can draw focus to temporality, transformation and experience in such devices.

We found paper as a material particularly interesting because of it can be fragile, tearable and degradable, all qualities that subvert the sense of permanence. However, most interactive paper projects push focus to the electronic components, with the paper as support material rather than an essential material with its own active capabilities. HCI research on flexible displays often reflects some affordances of paper [20], but the ability to tear, crumple, burn or biodegrade are typically neglected. While many if not all paper based electronics projects have explored the affordances of paper to some extent [21 - 24], even projects that integrate electronics during the papermaking process do not necessarily use the electrical properties of the paper itself [11]. It is also worth noting that, as late as 2010, in a paper researching manipulation and gesture in deformable paper like displays, such devices were asserted as a speculative technology [25]. The methods we introduce in this paper enables artists and designers to fabricate these once speculative displays in a studio with limited resources and demonstrate interactions based on the affordances of paper, responsive EL properties and ephemeral qualities.

2.3 Electroluminescent Paper

EL foils are a type of flexible, light emitting surface or display. Commercially produced EL is both flexible and thin, ideal for the backlighting of LCD displays, emergency signage and even in billboard advertisements. As with many smart materials, EL films are engineered to meet specific requirements for application and performance needs. For example, it is manufactured for backlighting of control panels in airplanes or cars. Thus, it has to provide a perfectly homogeneous light surface which will not disturb the pilot or driver. Reduction in electrical and audible noise, power efficiency and durability are also key requirements for such applications.

EL films are constructed from two electrodes sandwiching a dielectric and phosphor layer. When an alternating current is applied to the electrodes, a strong electrical field is created, resulting in light emitted from the phosphor (in our examples *copper doped zinc sulfide* which emits a green blue hue) [26]. Indium Tin Oxide (ITO) coated polymer is commonly used as a transparent electrode to allow this light to escape from the encapsulated phosphor. EL foil can be fabricated through screen-printing for cost effective mass production and it offers the advantage of flexibility, thinness and low power consumption over incandescent lighting. El wire is an alternative construction that works with the same principles as EL foil, but in a flexible wire format. The green/blue hue produced by the EL could draw comparison with bioluminescent organisms such as the Panellus Stipticus fungi, fireflies and marine microorganisms like Noctiluca Scintillans. However, commercially produced EL appears plasticy and highly homogeneous in contrast with these examples from nature.

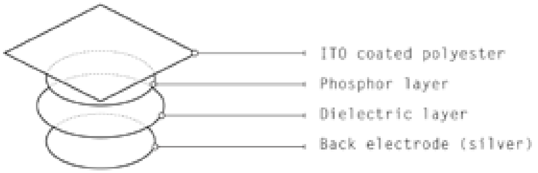


Fig. 1. A composition of commercially available EL paper.

Existing art and design projects use mainly these kinds of commercially available EL products. They are displayed with compositions of unaltered foils like the *Bourrasque* installation [27], cut into shapes as in the *Material Animation* workshop [28], or integrated in other materials and fabric such as *Functional Styling* [29]. Rachel Wingfield of Loop.ph design studio created custom screenprinted EL panels as early as 2002 and again in 2006 for the *History Tablecloth* [30]. Loop.ph also brought EL to an architectural scale by weaving EL wires into spatial structures with several projects such as *Spiratomic Space* [31].

3. Design Experiments

After an attempt using off-the-shelf EL, we decided to create our own EL paper from scratch in order to explore new aesthetic and interactive possibilities. In what follows, we describe design and fabrication experiments in which we worked against the homogeneity and plastic look that is characteristic of existing EL products. The results are surfaces that exhibit ephemerality, interactivity, fragility and other unique qualities. In addition to this, we cover two multimodal examples where we enabled motion and sonic capacities of the EL material.

3.1 Etching the Existing

Our attempt to work with commercially available EL foils was initiated by an invitation to develop a concept for a long term EL art installation. After having explored different bending and cutting methods, we focused on laser engraving. This method allowed us to customise the EL foil with various textures or graphical elements. Using a laser cutter we etched away the rear electrode to permanently deactivate certain areas of the EL foil with minimal visual artefacts on the front surface. The result was a surface that reveals patterns and shapes only when activated (Fig. 2). The pattern we created was motivated by our aesthetic goal of developing a water-like surface. We wrote a script for *Reaction Diffusion* based patterning to engrave into the surface, as the organic and fluid qualities of such designs closely aligned with our goal. Through this approach it was possible in one step to etch patterns while laser cutting areas in the EL sheet, thus quickly fabricating both complex structures and surface patterning. However, with this approach, the surface would always retain its plastic appearance. We realised that we can depart from such artificial characteristics in commercially available EL only through a more in depth, hands-on approach.

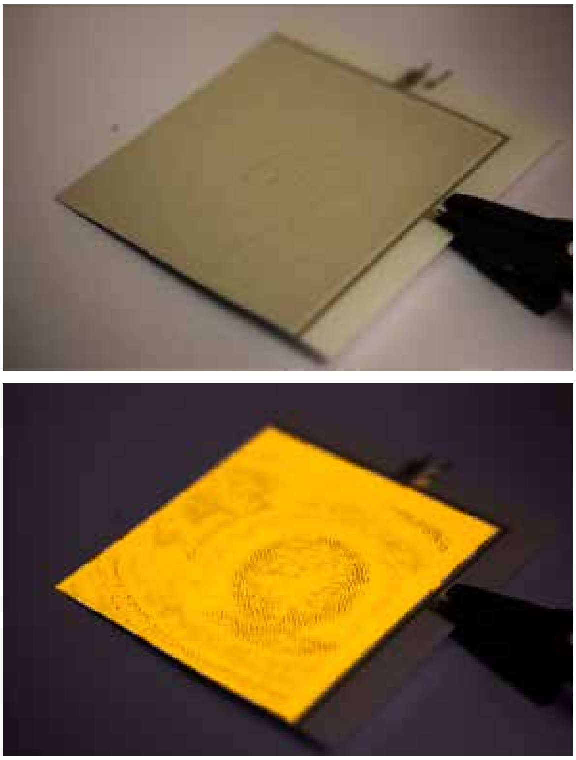


Fig. 2. EL foil with a Reaction Diffusion pattern etched on the rear electrode.

3.2 Reproducing industrial fabrication process

Our next step was to understand commercial fabrication processes and simplify them enough to be able to do it ourselves. In the *Actuated Matter workshop* [32], we collaborated with Loop.ph spatial laboratory, learning from their experience with screen-printing EL. We followed a methodical handcrafting process, which resulted in a luminous surface with an unexpectedly organic appearance (Fig. 3). Although the patterns were designed on computer and their stencils printed, the process allowed us to directly engage with the material during the screen-printing phase. Through irregularities in the hand printing process, we were able to get away from the homogeneity of the conventional EL. However, we were not able to address the plastic-like appearance with this approach.

Fig. 3. Screen-printing EL on ITO coated polymer during the Actuated Matter workshop.

3.3 De-plastifying

The plastic appearance comes from by the ITO coated polymer, the key component which provides a substrate and transparent conductivity required for EL. Thus, we set to explore the possibility of substituting the ITO with substrates like conventional paper. This introduced the need to experiment with alternative transparent conductive materials. Using paper as a substrate for EL devices has been proposed in the past [33], but never as an aesthetic exploration or in a way that would be accessible to designers. Our initial experiments to resolve this used diluted silver ink and carbon black powder, which both resulted in working EL displays on paper. In both cases the conductive material was not transparent, but the irregular coating had enough breaks and discontinuity to allow light to permeate through the opaque material. On both accounts the illumination was poor to the point of being barely visible. More enticing results were achieved by screen-printing silver ink with a matrix of ‘pores’ to allow the light to pass through (Fig. 4). The phosphor illuminated underneath the silver electrode, but because of the phosphor’s translucency a thin ring of light could escape from beneath the edges of the silver. Even though the total luminance is limited to the edges of the silver print, this approach allows effective printing of EL graphical elements and patterns on a paper substrate.

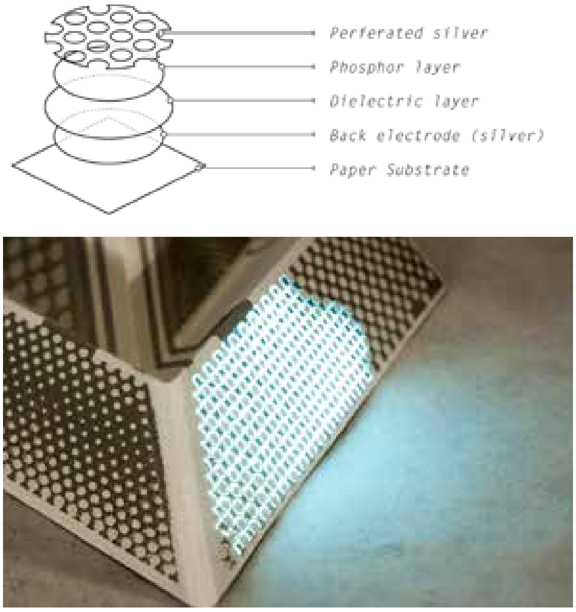


Fig. 4. EL printed on paper with perforated silver ink.

Eventually we tested a PEDOT based transparent conductive ink (gwent C2100629D1) which produced the strongest luminance from our EL paper tests and was significantly easier to handle and print than silver ink. This ink has faster drying and curing time than silver ink, which sped up our fabrication process significantly, opening up new opportunities for experimentation.
In contrast to the commercial produced EL foils,

these screen-printed surfaces retained all the material qualities of paper and exhibited intriguing imperfections and irregularities from the fabrication process (Fig. 5). Unlike other display technologies commonly referred to as electronic paper, EL paper truly allows for an exploration of affordances inherent to paper such as creasing, crumpling or tearing (Fig. 6). This opens up numerous new possibilities for interaction, some of which have been further explored in *PrintScreen* [34], which was inspired by our approach with EL paper and made use of our information and guidance.

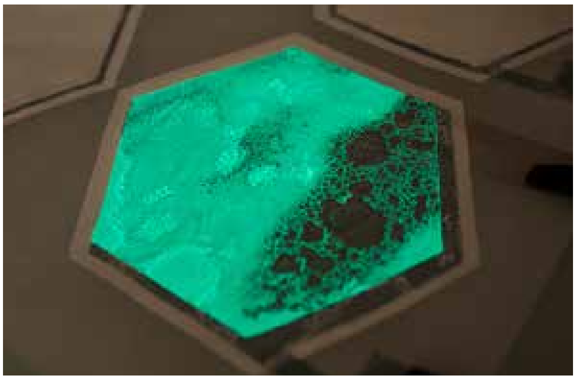


Fig. 5. EL printed with PEDOT based transparent conductive ink.

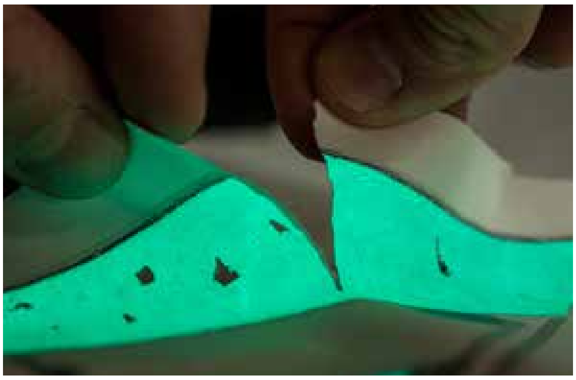


Fig. 6. Tearing the EL paper

3.4 Folding

With the new techniques covered in the previous section, we were able to create a foldable EL surface from a paper substrate (Fig. 7). We first developed a foldable structure based on a simple interconnected hexagonal arrangements in Grasshopper for Rhino 3D, a generative design tool. Folded structures are typically highly geometric, but the form we developed allowed for a more subtle, organic like modulations through its algorithmic generation. We fabricated the folded design with a flatbed plotter to pre-crease and cut the structure in preparation for printing. Five layers of print were applied to the paper, including back electrodes and traces, two layers of dielectric, phosphor, PEDOT ink and finally silver ink at the contact points between the paper and hardware. Simple snap fastener studs were used for interfacing between the paper and insulated wires for connection to the power supply. From here the structure was folded into its final form and illuminated with a sequenced animation using a custom built controller. The illuminated parts of the structure were resistant to a degree of folding, bending and contortion (see video at http://vimeo.com/84845032).

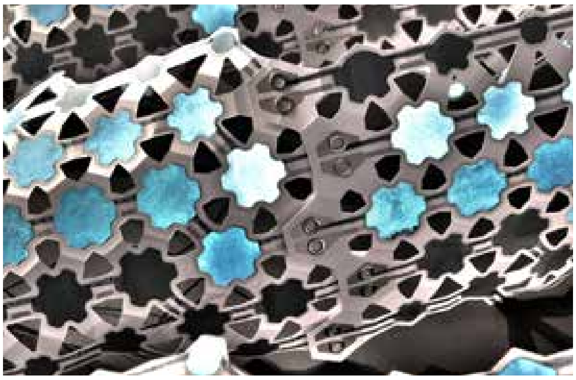


Fig. 7. EL surface printed on folded paper.

Our next challenge was to enable painting with luminous matter. By pre-printing the back electrode, dielectric and phosphor layers through screen-printing on paper, we hand-painted the transparent PEDOT ink directly onto the phosphor layer. This enabled us to quickly try out ideas and to explore the dynamic free-hand technique for generating luminous surfaces.

3.5 Paper as an Active Material

We further iterated the hand painting approach to produce an EL material where the paper itself is both the substrate and the dielectric material. This means that we reduced the layers that must be painted from five to three: back electrode, phosphor and front electrode. Uniformity in the dielectric layer is essential to avoid short circuits and poor EL performance. Since our approach uses the homogeneous thickness of the paper the remaining layers can be less precise. This allows the possibility of hand painting the entire surface, removing the complexity and time constraints of screen-printing. Through this approach the paper becomes an active part of the EL; it is no longer just a substrate material but an integral part of the EL

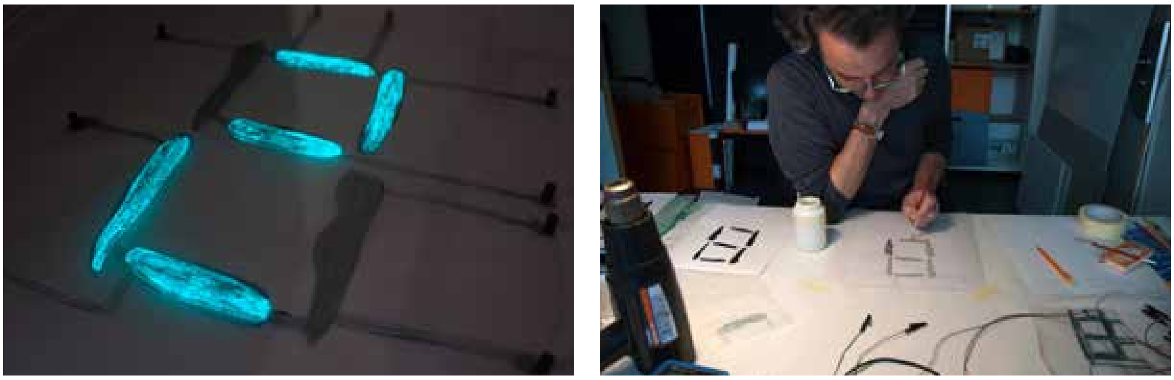


Fig. 8. Hand-painted numerical display, which "breathes" in a rhythmic fashion. A collaboration with product designer Robert Wettstein.

properties. We used tracing paper, which allowed viewability from both sides because of its translucency and for the unexpected effect of thin paper irradiating light (Fig. 8). This new technique allowed us to quickly involve designers without previous experience with EL in a creation process.

3.6 Painting Light with Water

As an ephemeral interaction experiment, we tested the use of water as an interface and as a transparent electrode (Fig. 9). Related interfaces using liquids include the *Soap Bubble* [35], where bubbles are the ephemeral material forming the interface between human and computer. In our case, however, the water is forming an interface between human and the material phenomena, avoiding any digital computation between interaction and visual response. Unlike printed or painted EL paper, the water electrode introduced a dynamic element to the lighting experience. The manipulation of fluid over the surface produced surprisingly animated and playful results. We moved the water, and therefore the appearance of light, by manipulating the paper through tilting and bending, dripping water via syringes and using a heat gun to move and evaporate the droplets. As the droplets of water connected and disconnected, new patterns of light began to flow and propagate (Fig. 10). Thus, we could interact directly with the affordances and agency of water, paper, electricity and light. Although this was one of the last experiments we did, we were filled with surprise and fascination as the light acquired a liquid appearance and behaviour (see video http://vimeo.com/104921022).

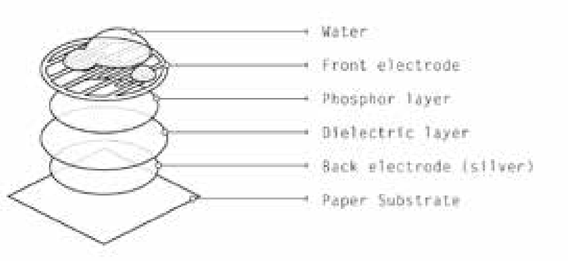
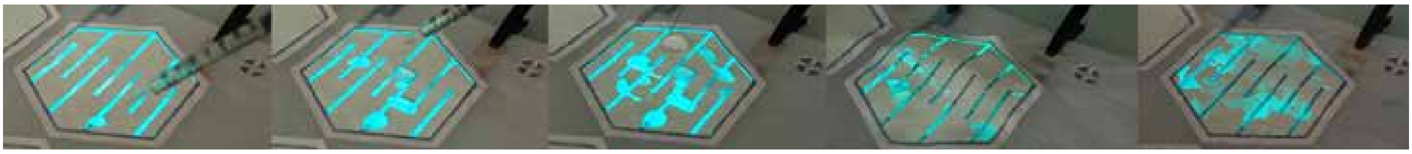


Fig. 9. EL construction using water as a responsive electrode.

3.7 Sounding Light

By taking a hands on approach to fabricating and experimenting with materials we are open to surprising and unexpected results. In one such example we accidentally discovered the possibility producing both light and sound when touching the EL surface (see video https://vimeo.com/60236646). After preparing a sheet of EL on paper, but before applying the last conductive layer, we placed a piece of ITO coated polymer over the phosphor and applied voltage. We were surprised to find that not only would the EL illuminate in response to pressure on the polymer, but a loud tone was also

Fig. 10. Video stills showing the process of creating illuminated areas by dripping and blowing droplets around the surface.



produced. This high frequency tone can be modulated by touching the surface.

The sound was the result of electroacoustic transduction. By separating the two electrodes an electromagnetic field results, vibrating the EL film in the same frequency as the alternating current from the EL driver. The driver used (ENZ E040 601X) is rated to output between 340-810Hz, which is incidentally and audible frequency range. The driver does not have a fixed frequency; it is free-swinging dependent upon the total capacitance of the attached EL film. The following formula expresses the output frequency, where L is the inductance at the driver and C is the capacitance of the screen [36].

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

When the module was pressed, the top electrode come into contact with the phosphor forming the capacitor. The more the surface was touched the greater the illumination and capacitance, resulting in reduced frequency i.e a lower pitch. The outcome was an eerie high pitch tone reminiscent of a theremin in its fluid modulation of sound.

All EL devices produce a subtle tone which can be heard when placed close to the ear. The alternating current produces an elastic deformation in the the dielectric at the frequency of the current oscillations [37]. EL devices designed specifically for the capability of generating sound were first proposed in 1989 [38]. However, the device was not touch responsive and it produced sound through a composite of piezoelectric ceramics and EL, rather than using the EL device itself to produce tone. In this example the ITO coated polymer was re-introduced, which we had previously avoided because of its undesirable qualities. Finding an approach which combines interactive capabilities of this device, with the material qualities of a purely paper based construction would be an exciting line of enquiry for further development.

3.8 Stretching Light

One of the most surprising experiments came from combining this work with another strand of our research, electroactive polymers (EAP) mentioned above, which deform when high voltage is applied (up to 5000v). In our process of constructing soft-frame EAPs, the stretched elastomer is applied to a compliant frame, which must oppose the force of the elastomers constriction but wield sufficiently to allow movement (see http://www.enactiveenvironments.com/enabling/tutorials-2/). The stretched surface is then manually impregnated on both sides with carbon black powder, forming two conductive electrodes separated by the dielectric elastomer. When voltage is applied the elastomer is constricted between the electrodes, relaxing the tension in the elastomer. Unlike the mechanical movement of most conventional actuators, EAPs have a fluid organic quality.

Using the same approach as in the “Paper as an Active Material” example, we painted a functioning EL surface on to the stretched dielectric elastomer (see video

Fig. 11. EL surface hand-painted on to a dielectric elastomer.

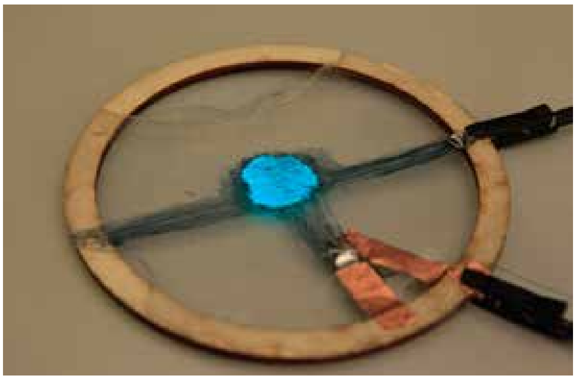
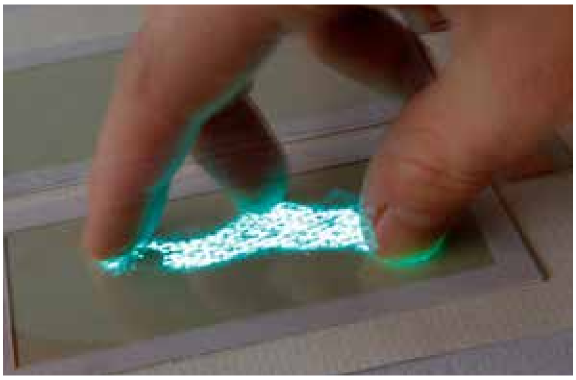


Fig. 12. Touch responsive, sounding EL surface.



http://vimeo.com/76430662). This simple experiment showed a potential for the combination of EAP and EL into one single material, a luminous surface that changes its form based on electrical activation. Such a material could potentially be used as a digital display in product design and architecture as it opens up rich possibilities for creative exploration of this soft, moving, transparent material.

4. Conclusion

Existing projects in interaction design are dominantly based on combining, composing or weaving of ready-made electronic components - techniques which do not allow an exploration of active and responsive properties of matter. In this paper, we presented novel techniques for working with such matter in the case of EL paper. We explored its unique aesthetic and ephemeral qualities by developing a number of novel materials and unique fabrication procedures. We reduced the process of creating EL paper from hours to minutes, further shifting the process away from the commercial fabrication to that of instantaneous handcrafting and exploration of EL paper. We described new possibilities for interactivity, creating audiovisual feedback to touch and modulating light through water. We also showed the possibility of integrating shape changing and luminescent behaviour into a single material. These examples demonstrate the power of our approach to engender novel creative practices and to engage designers with the aesthetics of ephemerality and responsiveness.

Our research revealed unexpected aesthetic potentials of EL materials. We embraced the benefit of relinquishing some control of the outcome, letting the materials show us their unexpected properties and guide our aesthetic explorations. We probed different physical assemblages and chemical conditions in order to alter material appearance and behaviour. We focused on properties and processes that are inherently present in such materials. Our approach was to activate such aesthetic qualities hidden in the material - thus the term *Active Materials.* This often led us to work with aspects that might be considered undesirable in some performance oriented applications, yet provided intriguing possibilities for creative contexts.

However, our aesthetic explorations would not have been possible without the knowledge gained from scientific resources and experts whose work is performance oriented. Dr. Emil Enz, who introduced us to commercial EL production was at first dubious of our methods, but as he saw the results he recognised new applications based on non-uniform EL for more natural lighting and interactive possibilities. This shows a potential for collaboration with material scientist and engineers: novel materials can feed into design research and, vice versa, design experiments can stimulate the development of novel materials.

This feedback hints at the potential for applications resulting from research presented in this paper, although we focused primarily on processes and materials themselves. By working with material transformation one is continuously pulled to investigate various possibilities, rather than to freeze processes into a fixed form or interaction model. For this reason our results did not take the shape of final products, commercial applications and larger scale pieces. We see this as our next challenge. We aim to embed the different techniques presented here into concrete projects involving users. Particularly important are the ephemeral aspects of EL paper and ways of integrating their aesthetics in everyday life and exploring their interconnectivity with the environment (for example, exposing an EL paper to rain and let it draw light surfaces with its drops).

The evaluation of our experiments was naturally embedded in the research process as we discussed and made decisions on what kinds of aesthetic effects are worth following. We did not follow a structured perceptual evaluation, but let the process evolve naturally as we acquired an intimate aesthetic knowledge of materials. We did however involve other designers and students in our work. The documentation of our experiments allowed us to reproduce the findings and to share them through our online platform and in hands-on workshops [39]. By inventing novel fabrication processes, we were able to transfer this knowledge from research labs into the hands of designers who provided valuable inputs in the form of direct feedback. Our future steps include the development of evaluation methods to understand the affective and aesthetic impact of a specific material on both designers and users.

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