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Fabrication technologies for the integration of thin-film electronics into smart textiles

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DOI: 10.1533/9780857093530.2.227

Abstract: Smart textiles are a key component for sensing physiological parameters close to the human body, supporting and assisting people in daily living. In addition, smart textiles offer potential in technical textiles: they comprise car and airplane interiors where lighting and emergency signaling are potential applications, in bandages for wound monitoring or automatically adjusting furniture in homes. The chapter starts with an introduction outlining the state-of-the-art smart-textile production. Then the processes for the fabrication of electronics on flexible plastic stripes, mechanical requirements due to the integration into woven textiles and the integration method of the flexible stripes into woven textiles are described. The feasibility of the technology is demonstrated with three prototypes: one prototype measures humidity and temperature, the second one has an integrated bus system and the last one is a textile integrated active matrix with light emitting diodes. At the end of the chapter, potentials of the technology are described to overcome issues related to smart textiles production, such as user acceptance, washability or large-scale production.

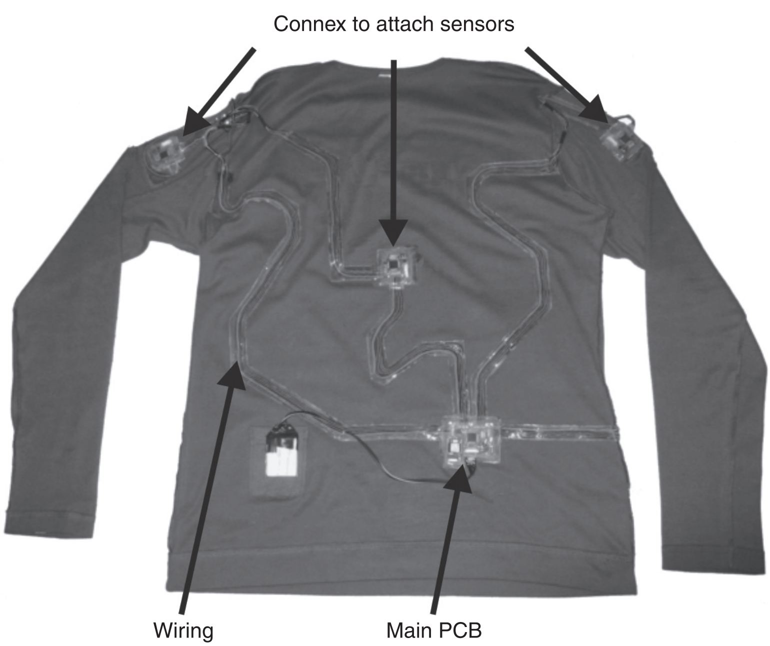
Key words: smart textiles, flexible plastic substrate, thin-film device.

8.1 Introduction

Integrating sensors or general electronics into textiles enables ubiquitous sensing to support people in their daily life. The sensing tasks involve physiological signals as well as environmental parameters for assistance in healthcare and rehabilitation, sports and high-risk professions such as fire fighting (van Langenhove and Herteleer, 2004; Paradiso *et al.*, 2005; Mattmann *et al.*, 2007). Textiles, which are usually worn close to the body, provide a suitable platform to integrate all kinds of electronics to measure physiological signals and environmental parameters. However, such textiles with integrated electronics will only succeed if they are accepted by the users requiring an unobtrusive and seamless integration of the electronics in the textiles. Moreover, smart textiles enable other fields of applications: one is technical textiles comprising for example carpets, curtains or car interiors (Savio and Ludwig, 2007). As for body worn textiles, unobtrusive integration of the electronics is required to maintain the look and the feeling of textiles. Another field is textiles for medical applications such as bandages.

A common approach to fabricate smart textiles is based on printed circuit boards (PCBs)[1] attached to a textile. The PCBs serve as substrates for microprocessors, sensors and data storage units (Park *et al.*, 2002; Harms *et al.*, 2008; Locher and Tröster, 2007a; Martin *et al.*, 2009). As an example, the Smash shirt (Fig. 8.1), developed for upper body position monitoring, consists of a main PCB containing a microprocessor and plugs for acceleration sensor units. The sensor units are distributed over the whole shirt and connected with the main PCB using cables to store the acquired data on a single device (Harms *et al.*, 2008). Attaching PCBs to textiles renders parts of the textiles rigid, which reduces the comfort of the wearer. In Linz *et al.* (2007), flexible PCBs are applied to reduce the rigidity of the textile.

To establish interconnections between individual PCBs on textiles, several methods are applied: one approach is to integrate insulated copper wires into textiles during weaving (Locher and Tröster, 2007b; Martin, 2009). Other approaches are screen-printing of silver paste on textiles (Locher and Tröster, 2007b), gluing insulated copper wires onto textiles (Harms *et al.*, 2008), encapsulate meandering copper lines into polymer and attach the whole structure to textiles (Gonzalez, 2008) or use embroidery (Linz, 2007).



8.1 Smash shirt, with main PCB for data storage, and wiring to connect to the connex, where the sensors are plugged in.

A different approach to fabricate smart textiles is to integrate electronic devices such as resistors or transistors into single threads (Bonderover and Wagner, 2004; Abouraddy *et al.*, 2007; Hamedi *et al.*, 2007). This approach of integrating electronics into textiles is unobtrusive, but the circuits achieved so far consist of a maximum of two transistors. The aim of this section is to describe a different approach to integrating electronics into woven textiles using flexible plastic stripes, which comprise electronics in the weft direction. Conductive textile threads in the warp direction are used to interconnect the flexible stripes. In Section 8.2, the basic ideas of the technology are described, as well as the required process steps of fabricating the electronics and merging them with woven textiles. In Section 8.3, the feasibility of the technology is presented with three prototypes. Section 8.4 addresses aspects of the mechanical stability of plastic stripes with electronics woven into textiles. Sections 8.5 and 8.6 give an outlook on possible contributions of the technology to the field of smart textiles and resources to find further information.

8.2 Merging flexible electronics and smart textiles

As described in the Introduction, a common approach to fabricate smart textiles is attaching rigid PCBs to textiles and establish interconnects among the PCBs by using, for example, copper wires. The attached PCBs offer the possibility to integrate sensing systems with processing and storage capabilities on textiles, but they also introduce rigid parts in the resulting textiles, which reduce the comfort of the wearer.

The goal of merging flexible electronics and textiles is to develop a technology that combines the advantages from both the electronics and textile world. The electronics integrated into textiles should be capable of sensing and transmitting the recorded signals while the textile remains bendable and drapable. In addition, the technology should rely on existing processes to be compatible with standard machinery and production facilities from both the electronics and the textile fabrication chains.

The technology presented in this section makes use of the inherent x-y grid structure of weft and warp threads of a woven textile. In the weft direction, flexible plastic stripes, called e-stripes, are integrated during the weaving process into textiles. E-stripes serve as substrates for various kinds of electronics such as thin-film devices,[2] surface mount devices (SMDs) and integrated circuits (ICs). Furthermore, the e-stripes provide interconnect lines between the electronics and contact pads on the e-stripe. In the warp direction, conductive textile threads are used to establish connections among the contact pads on individual e-stripes to generate electronic systems integrated into woven textiles.

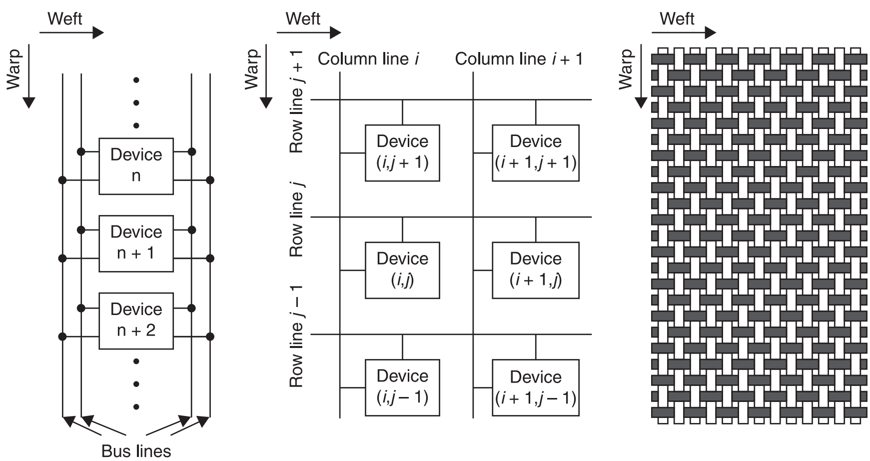
8.2.1 Technology principles

The x-y grid structure of warp and weft threads in woven textiles is beneficial for electronics integration, because electronic bus systems and matrices are arranged in a similar grid structure. Figure 8.2 shows an exemplary bus system, a matrix and schematically the structure of a woven textile. Bus and matrix systems are used to control sensors and actuators in an efficient way by sharing interconnect lines.

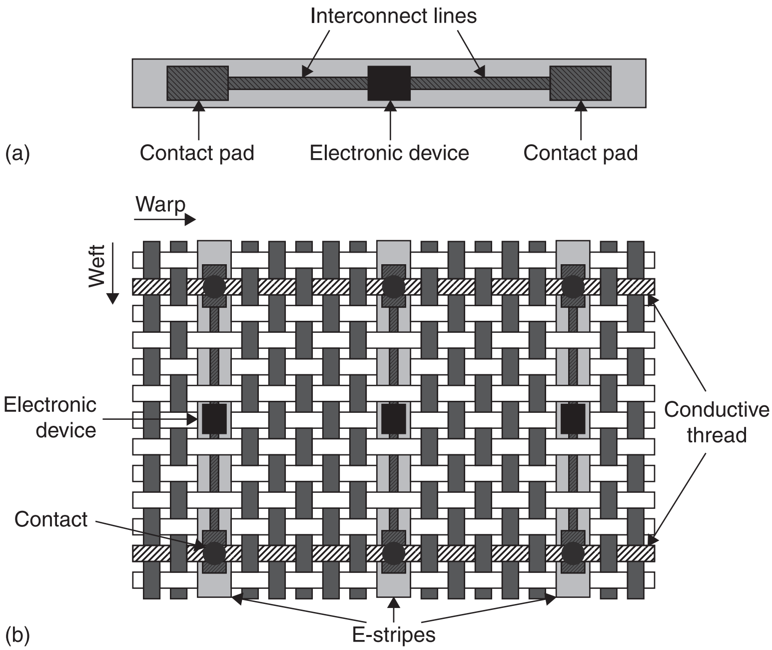
In a bus system (Fig. 8.2(a)), a number of devices, here labeled as 'Device n' to 'Device n+2', are interconnected with shared lines for communication and power supply. In Fig. 8.2(a), four bus lines are shown. However, depending on the communication scheme among the individual bus devices, this number can vary. Common bus systems are I^2C and SPI. Both bus systems require four shared lines, of which two are used for power supply and the other two for communication. Another example is the 1-Wire protocol, which requires two lines, one for common ground and one for communication and power supply.

A matrix system (Fig. 8.2(b)) consists of n columns and m rows. At each crossing point of a column line and a row line, an electronic device is located, which can be individually selected by sending an electrical signal on the specific row and column lines. As an example, when row number j and column number i are enabled, Device(ij) is selected. A prominent application of matrix systems are flat panel displays, where each individual pixel is controlled by selecting specific row and column lines (Crawford, 2005).

To integrate electronics into textiles, the inherent arrangement of warp and weft threads is used (Fig. 8.2(c)). The warp direction is used to integrate conductive threads, which serve as bus lines or as column lines in a matrix system. The weft direction of woven textiles is used to integrate flexible plastic stripes during the



8.2 (a) Bus system with n devices connected to four shared bus lines. (b) Example of a matrix arrangement with two columns and three rows. (c) Arrangement of warp and weft threads in a woven textile, showing the similarities to the electronic bus and matrix system.



8.3 (a) Schematic of an e-stripe with an electronic device, interconnect lines and contact pads for conductive warp threads. (b) Schematic of the approach to integrate electronics into woven textiles. In weft direction, e-stripes are integrated and in warp direction, conductive threads are woven and contacted to the e-stripes. The white threads in warp and dark grey threads in weft are non-conductive textile threads.

weaving process. The e-stripes, providing a basis for electronics, are processed using clean-room techniques before weaving. The e-stripes serve as carriers for ICs, thin-film sensors, thin-film transistors (TFTs), interconnect lines and contact pads for the conductive threads in the warp direction. Figure 8.3(a) shows a schematic of an e-stripe containing an electronic device, interconnect lines and contact pads for the conductive threads. E-stripes in weft and conductive threads in warp are interspaced with standard non-conductive textile threads. After weaving, an electrical contact is established between the contact pads on the e-stripes and the conductive threads. In addition, the electrical contact is mechanically reinforced. Figure 8.3(b) shows the principle of the technology.

The integration of e-stripes based on flexible plastic substrates in the weft direction offers several advantages, besides the ability to carry electronics:

- Flexible stripes enable the reduction of rigid areas in smart textiles compared to PCBs.

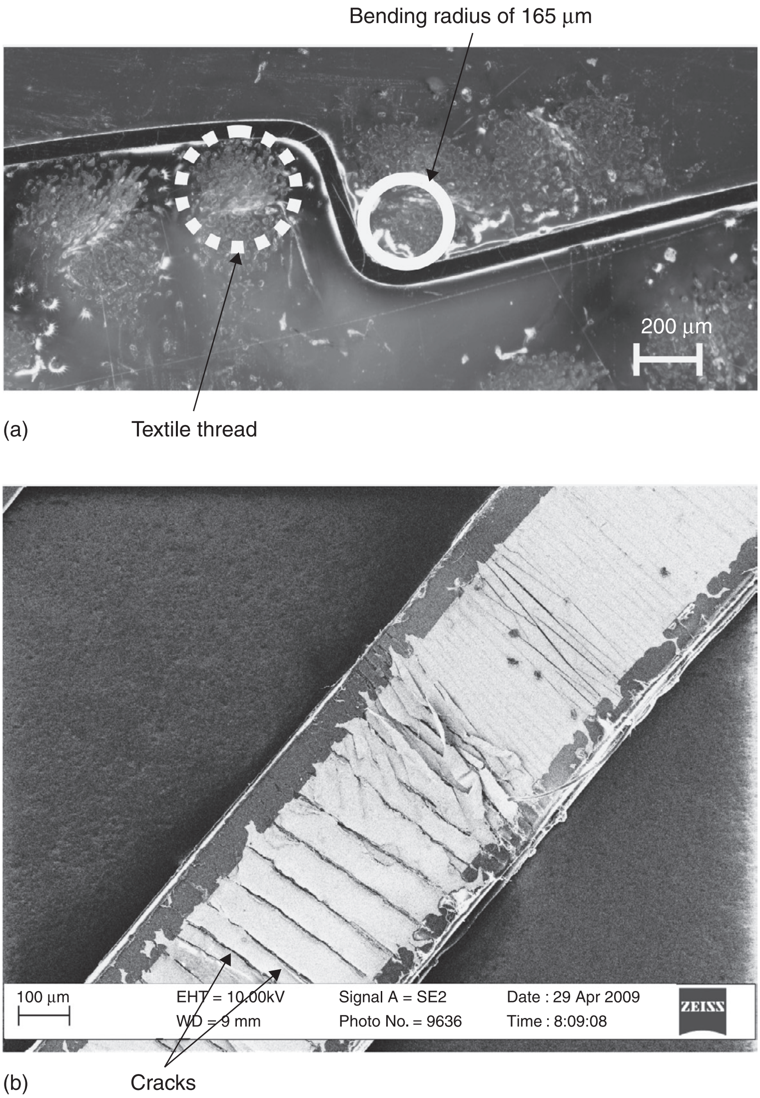
- Metal layers on e-stripes enable the fabrication of contact pads and wiring among individual components on the e-stripe, as well as a flexible distribution of the electronics on the surface by selective patterning of the metal layer on the e-stripe (Crawford, 2005; Cherenack *et al.*, 2010a).
- Flexible substrates and hence e-stripes are a suitable platform for a variety of devices and circuits. They can range from thin-film devices, like transistors or sensors, to bare dies (semiconductor chips without packaging) and small SMDs.
- Due to the integration in the weft direction, the location of the e-stripes in the textile can be chosen freely, compared to integration in warp direction where a change of the warp beam would be necessary to change the location of the electronics.
- Flexible substrates offer the potential for large-scale production by applying printing or roll-to-toll techniques[3] (Service, 1997).

All these advantages converge in two essential attributes of this technology: first, the location of the electronics on the e-stripes is variable as well as the location of the e-stripe and hence the electronics in the woven textile. Second, the electronics can be chosen from a wide range of devices, such as SMDs, thin-film devices and bare die chips.

8.2.2 Stripe fabrication

Fabricating e-stripes, which serve as substrates for sensors, interconnect lines and contact pads, comprise the following steps: cleaning of the substrate surface, deposition and structuring of material layers, cutting the substrate into stripes and, if required, attaching SMDs or bare die ICs. As a base material for the e-stripes, a 50 μm thick polyimide foil, in particular Kapton E (from DuPont), is used. Kapton was chosen as the substrate due to its comparatively low coefficient of thermal expansion (CTE) of 16 ppm per °C, a high glass transition temperature (T_g) of 355 °C, which allows process temperatures of up to ca. 300 °C, and its stability against solvents, which are used in further processing steps (Kapton, 2011).

Before material layers are deposited onto the Kapton foil, a thorough cleaning is necessary to ensure a stable adhesion of the subsequent material layers. A stable adhesion of the material layers on the flexible substrate is needed, because woven e-stripes are exposed to bending radii as small as 165 μm (Fig. 8.4(a)). A bending radius of 165 μm of a 50 μm thick substrate imposes a strain of ca. 12% on the material layer on the substrate (Suo *et al.*, 1999). In the case of deposited material layers made of gold, copper or titanium, a strain of 12% causes cracks in the metal layers (Fig. 8.4(b)). The cracks can emerge, of course, from brittle material layers, but also from improper adhesion caused by dust particles or other remnants between the plastic substrate and the deposited material layers. Dust particles and other remnants cause tiny areas where the two layers do not adhere and the strain

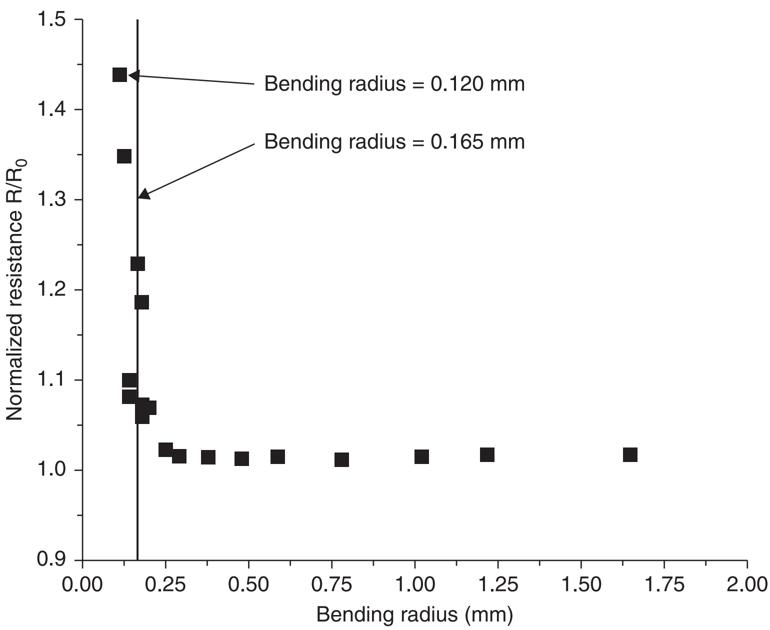


8.4 (a) Cross section of a woven textile with an integrated e-stripe. The e-stripe is exposed to bending radii as small as 165 μm corresponding to strains of up to 12%. (b) SEM picture of a cracked metal layer after weaving. The cracks occur because no cleaning step was applied before layer deposition.

is localized. Therefore, a cleaning step is required to prevent cracking (Cherenack *et al.*, 2010b).

During the cleaning process, dust particles and other remnants on the surface of the substrate that reduce the adhesion are removed. In addition, heating, which is also a part of the cleaning process, removes trapped solvents in the Kapton foil. First, the Kapton foil is sonicated in acetone and isopropanol (IPA) for 10 min. Sonicating is a process where the liquid, in the present case the acetone and IPA, are actuated with ultrasound. The mechanically actuated liquid promotes the physical removal of dust particles and remnants on the surface of the plastic substrate. To remove the trapped solvents and other small molecules, the plastic substrate is stored at 200 °C for 24 h in a vacuum oven. Furthermore, the substrate is then exposed to oxygen plasma for 3 min to activate the substrate surface and further promote the adhesion of subsequent material layers (Lin and Liu, 2008).

The effectiveness of the cleaning process was tested by fabricating 1 mm wide stripes with a 500 μm copper layer on top. The stripes were bent between two movable plates. While the bending radius was decreased, the resistance of the copper layer was measured. The results of these measurements are shown in Fig. 8.5, with the resistance normalized to the resistance of the copper layer without applied bending radius. The cleaning method allows bending radii as small as 120 μm, which is smaller than the measured bending radius of 165 μm in woven textiles. At radii smaller than 120 μm, the copper layer starts to crack (Cherenack, 2010a).



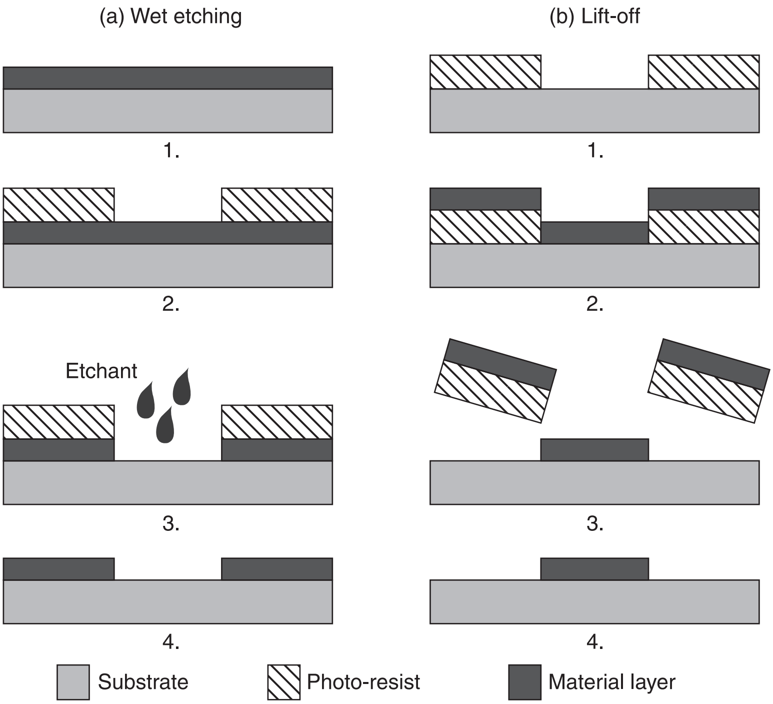
8.5 Bending radius versus normalized resistance of a 500 μm copper layer on a 50 μm thick Kapton substrate. At radii smaller than 120 μm, the copper layer starts to crack. As a vertical line, the smallest measured bending radius of 165 μm in woven textiles is indicated.

After cleaning, material layers such as metals, insulators, organic materials and semiconductors are deposited and structured on the flexible substrate. For the material deposition, several methods are applied:

- *Electron beam evaporation*: The workpiece is placed in a vacuum chamber. Within this chamber, an electron beam (e-beam) is used to heat up a target material such as gold, titanium etc. The electron beam causes atoms of the target material to evaporate. The vapor is distributed in the whole vacuum chamber and precipitate on the workpiece as well as other parts in the vacuum chamber in line of sight.
- *Sputtering*: To deposit material on a substrate with sputtering, the workpiece is placed in a vacuum chamber. Plasma is guided on the target material to evaporate it. The material in the vapor phase transits from the gaseous state back to the solid state and covers the workpiece and the rest of the chamber. Sputtering is used to fabricate oxide semiconductors, such as indium-gallium-zinc-oxide (IGZO), which are used for (flexible) TFTs (Yabuta *et al.*, 2006, Münzenrieder *et al.*, 2011).
- *Spin-coating*: To spin a coating onto a substrate, the coating material is placed in dissolved form on the substrate. By spinning the substrate, the dissolved material starts to expand and cover the whole surface of the substrate, resulting in a uniformly thick material layer. After spin-coating, the material is irradiated or heated to remove the solvents, leaving a layer of the desired material.
- *Atomic layer deposition (ALD)*: The workpiece is placed in a vacuum chamber. Normally two reactive gases are subsequently led into the chamber. Both gases react on the surface and result in a single atomic layer of the desired material. By repeating this process, several atomic layers are deposited.

To fabricate interconnect lines, contact pads, sensors, TFTs, etc. the deposited material layers on the flexible substrate need to be structured. Structuring the material layers is achieved by using the following techniques:

- *Etching*: Figure 8.6(a) shows an etching process. First, a material layer is deposited on the substrate. In a second step, a photo-resist is spin-coated onto the material layer. The photo-resist is structured by using a mask, which covers parts of the photo-resist and exposing it to UV-light and dipping it in a developer. Then, the substrate is exposed to an etchant, which removes the parts of the material layer not protected by the photo-resist. Finally, the remaining photo-resist is removed using an appropriate solvent.
- *Lift-off*: Figure 8.6(b) shows a lift-off process. In the first step, photo-resist is spin-coated onto the substrate and structured in the same way as for etching. Second, a material layer is deposited on the whole workpiece. In the third step, the workpiece is dipped into a solvent bath, which dissolves the photo-resist. The material layer, which is on top of the photo-resist, is removed with the photo-resist, leaving behind the desired structure on the substrate.



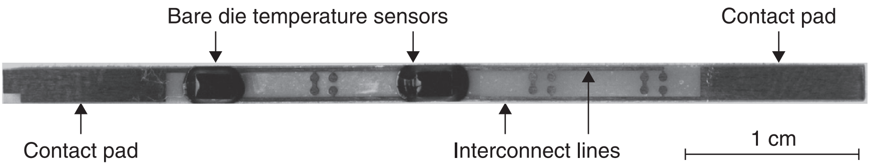
8.6 (a) Shows the process steps for wet etching to structure a material layer. In (b) the main steps of a lift-off process are depicted.

The deposition and structuring methods described here are the ones that are used to fabricate e-stripes. However, they are only a selection among a large variety of available processes (Menz *et al.*, 2001).

After depositing and structuring material layers, the substrate is separated into individual stripes. For cutting the substrate, a wafer saw with a diamond blade is used. This method allows the fabrication of stripes as narrow as 50 μm, with a deviation from the cutting path of less than 7 μm (Kinkeldei *et al.*, 2009). When bare die ICs or SMDs are required on the e-stripes, they are attached by soldering or gluing with a conductive adhesive. The devices are protected using glob-top (epoxy resin), which is cured for 1 h at 100 °C. In Fig. 8.7, an example of a separated e-stripe with contact pads for conductive threads, interconnect lines and two digital temperature sensors mounted on the e-stripe is depicted. The stripe is 2 mm wide and 4.5 cm long.

8.2.3 Weaving

The stripes are woven into a 4.5 cm wide textile band using a commercial weaving machine of type NFREQ 42 from Müller Frick. Prior to weaving, conductive threads are integrated into the warp beam. The conductive threads in warp



8.7 Exemplary e-stripe with contact areas, interconnect lines and bare die integrated circuit digital temperature sensors.

direction serve, for example, as bus lines (for a bus system) or as column lines (in a matrix system). For the demonstrators, which are shown later in this section, the conductive threads are knotted into the warp beam. To ensure that the conductive warp threads cross the contact pads on the e-stripes, it is necessary that the conductive threads are part of the same heddle frame.

Inserting an e-stripe into the textile involves several steps, which are specifically tailored for the demonstrators:

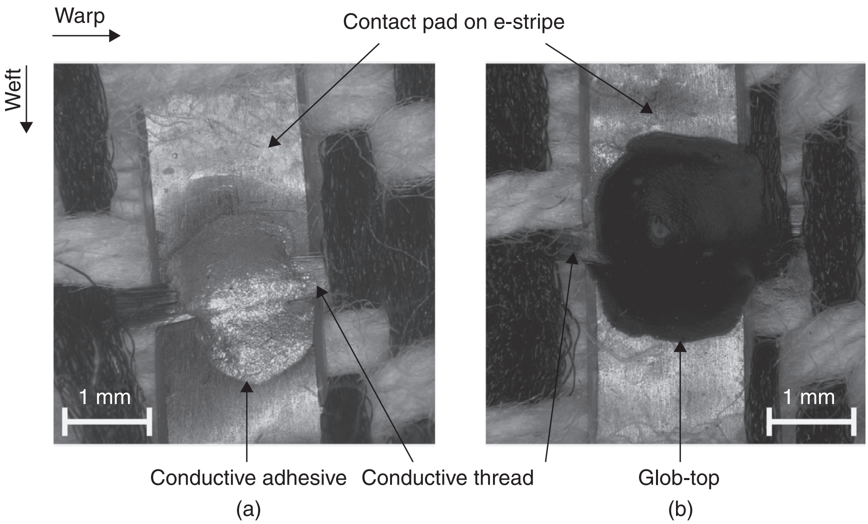
1. The weaving speed of the machine is lowered.
2. The insertion of weft threads is blocked by stopping the weft thread feed to open space in the textile for the e-stripe. The number of blocked weft threads is equal to the weaving density (threads/mm) multiplied with the width of the e-stripe (mm). For the used weaving machine, the weaving density is set to 2.5 weft threads per mm and the exemplary stripe from Fig. 8.4 has a width of 2 mm, resulting in 5 omitted weft threads for this particular e-stripe.
3. To insert the e-stripe into the textile, the weaving machine is stopped and the e-stripe is inserted manually into the weaving machine. During the insertion, the contact pads on the e-stripe have to be aligned against the conductive threads in the weft direction to enable contacting after weaving.
4. The weaving machine is run in slow mode for at least two weaving cycles, to ensure that the textile is woven correctly and the e-stripe is not damaged. Then the weaving speed is increased.

The described steps are repeated for each e-stripe.

This weaving process is tailored to the used band weaving machine and the fabrication of the demonstrators. However, the process can be generalized for large-scale weaving machines and has to comprise the following steps: first, the machine has to open space for the e-stripes. Second, the stripes have to be inserted into the textile and aligned against the conductive warp threads. Finally, non-conductive textile threads have to be woven until the next e-stripe is inserted.

8.2.4 Contacts

After weaving, the contacts between the contact pads on the e-stripes and the conductive threads in the warp direction have to be established. For the



8.8 (a) Electrical contact with conductive adhesive between conductive thread in warp direction and contact pad on e-stripe in weft direction. (b) The electrical contact covered with glob-top for mechanical reinforcement.

demonstrators, this is done by using a silver-filled epoxy adhesive (Epo-Tek H20E), which is cured for 24 h at 60 °C to establish an electrical contact. To mechanically reinforce the contact, glob-top (Epo-Tek 7139) is used and cured for 1 h at 100 °C. Figure 8.8(a) shows an exemplary electrical contact with conductive adhesive and Fig. 8.8(b) shows the contact covered with glob-top. As for weaving, the process of establishing the contacts can be generalized. First, an electrical contact has to be established using, for example, soldering or gluing with a conductive adhesive and second, the contact should be mechanically stabilized by using epoxy.

8.3 Demonstrators

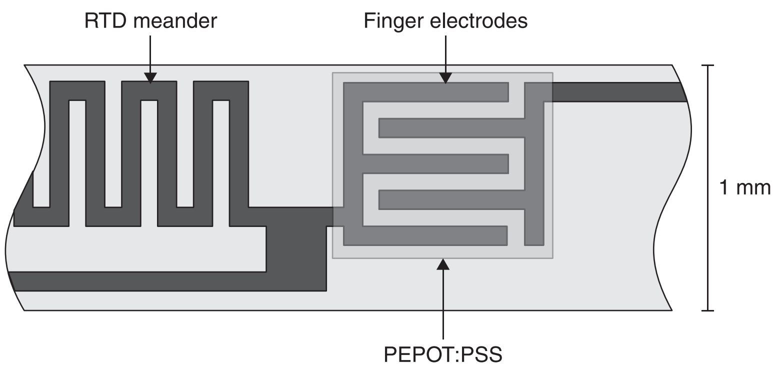
The feasibility of e-stripe technology is demonstrated with three prototypes: the first, which is able to sense temperature and humidity, consists solely of thin-film devices and does not require conductive threads in the warp direction. The second incorporates a bus structure in the woven textile and uses bare die ICs as bus devices. The last prototype is a matrix structure, which combines thin-film devices and SMDs.

8.3.1 Temperature and humidity sensitive textile[4]

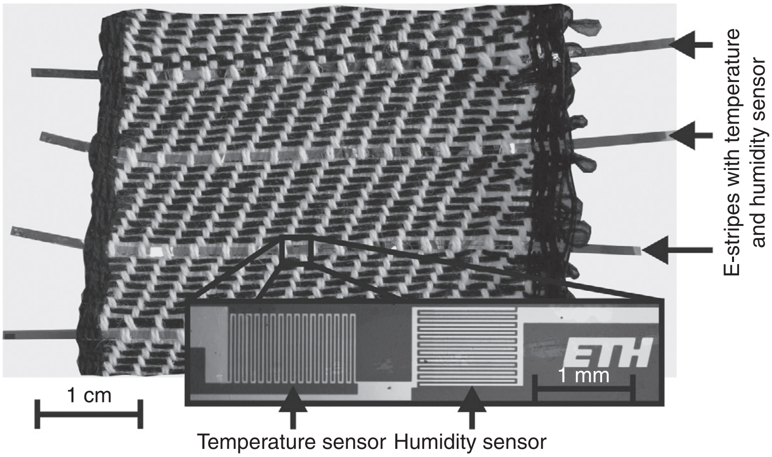
The integration of thin-film devices into a woven textile is demonstrated with temperature and humidity sensors on e-stripes. The sensors are designed to fit on a 1 mm wide stripe. To measure the temperature, a resistance temperature device (RTD) was used. The sensing principle is based on the fact that metals change their resistance, depending on their temperature characterized by the temperature coefficient α[5]. The humidity sensor is based on the conductive polymer PEDOT:PSS (Baytron P AI 4083), which absorbs water molecules leading to a change in the resistance of the polymer. The RTD shows a meander shape with a line width of 20 μm and a spacing of 20 μm. The total length of the RTD is 22 mm. For the humidity sensor, finger electrodes are used with a length of 1 mm, a spacing of 20 μm and 40 fingers. The fingers are covered with the conductive polymer PEDOT:PSS. Three interconnect lines are used to contact the sensors. These interconnects are routed to both ends of the e-stripe, to enable contact after weaving using standard copper wires. A schematic of the sensor part of the e-stripe is shown in Fig. 8.9.

To fabricate the sensors, a 7.6 × 7.6 cm^2 Kapton E substrate is used. After the cleaning process (Section 8.2.3), to achieve sufficient adhesion of the material layers on the substrate, 5 nm of titanium and 100 nm of gold are deposited using e-beam evaporation. The titanium/gold layer is structured to form the meander of the RTD, the finger electrodes for the humidity sensor and interconnect lines for contacting the sensors using a lift-off technique. In the next step, PEPOT:PSS is spin-coated on the structured electrodes with 1200 rpm for 1 min. The PEDOT:PSS film is dried for 10 min at 180 °C on a hotplate. The resulting thickness of the polymer film is 80 nm.

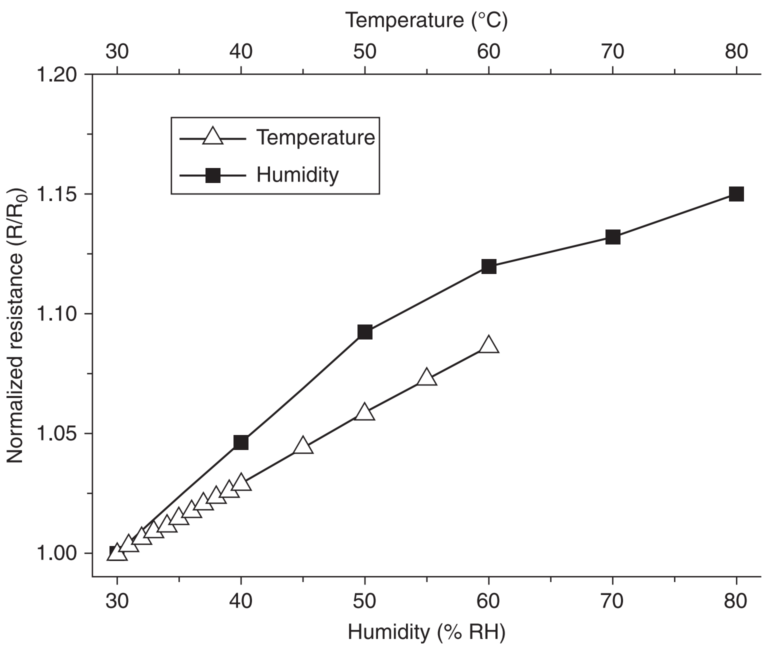
The substrate is then cut into 1 mm wide stripes using a wafer saw and woven into a textile (Sections 8.2.3 and 8.2.4). The resulting textile and a photo of the sensors are shown in Fig. 8.10. The functionality of the textile integrated sensors was tested in a climate chamber at temperatures between 30 and 60 °C and humidity between 30%RH and 80%RH. Figure 8.11 shows the measured



8.9 Schematic of the sensor part of the e-stripe with the finger electrodes and the PEDOT:PSS for the humidity sensor and the meander-shaped resistive temperature device.



8.10 Prototype of temperature and humidity sensitive textile. The inset displays the sensor area of the integrated e-stripe with the meander-shaped temperature sensor and the PEDOT:PSS humidity sensor.



8.11 Sensor responses for the temperature and humidity sensitive textile, obtained in a controlled environment of 30 to 60°C with a constant humidity of 50 %RH for the temperature sensor characterization. For the humidity sensor characterization, the humidity was varied between 30 and 80%RH at a constant temperature of 30°C.

resistance values for both sensors. The resistances are given normalized to the initial resistance values at 30 °C and 30%RH, respectively. The resistance values for the RTD show a linear behavior with a temperature coefficient α of 0.0028 °C^{-1}. The PEDOT:PSS based humidity sensor exhibits a linear behavior below 50%RH. Above 50%RH, a non-linearity is observed, which is caused by a water layer in the sensor material reducing the sensitivity of the sensor and hence decreasing the resistance change (Kus and Okur, 2009; Kinkeldei, 2011a).

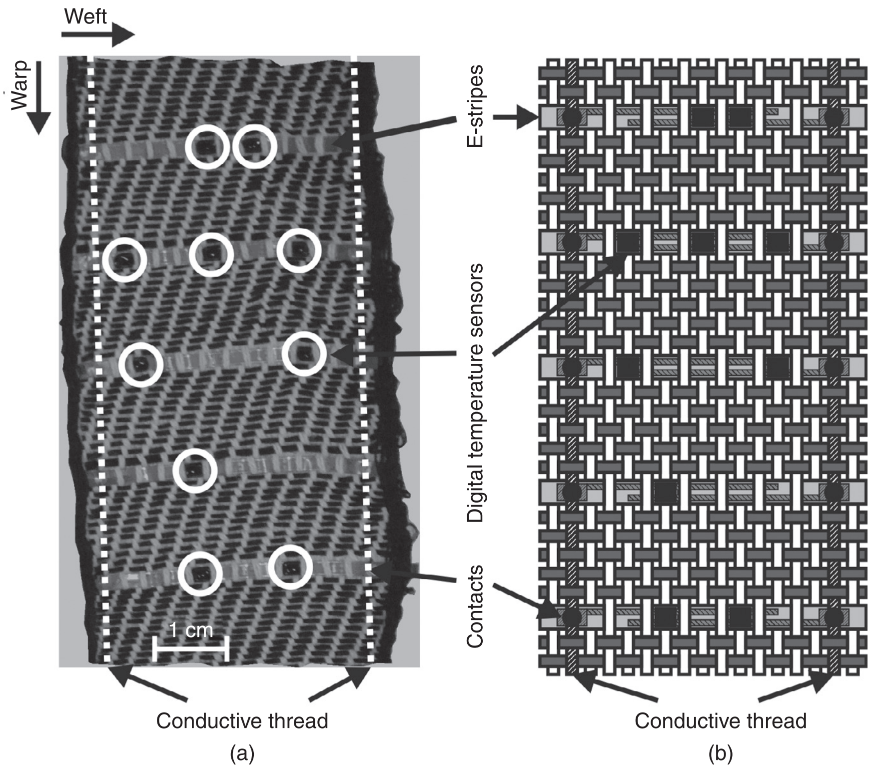
8.3.2 Textile integrated bus system[6]

To address a multitude of devices and in particular sensors in a textile, a bus structure (Fig. 8.2(a)) is applicable. For the integration of a bus structure into a woven textile, the weft direction is used to integrate e-stripes with the bus device, interconnect lines and contact pads. In the warp direction, conductive threads are integrated as bus lines. The integration of a bus structure is demonstrated with 5 e-stripes, which contain 1 to 3 bare die temperature sensors per e-stripe, resulting in a total of 10 sensors in the textile. The temperature sensors include the 1-Wire bus protocol (DS18S20, Maxim-IC (Maxim)), allowing sensor read-out and power supply with only two bus lines. One line is used for ground, the other for power and data communication.

The e-stripes are fabricated on Pyralux, which is a 25 μm Kapton foil sandwiched between two 18 μm copper layers (Pyralux, 2011). From a base substrate with a size of 4.5 cm × 6 cm, the bottom copper layer is completely etched away while the top copper layer is structured to form interconnect lines, contacts to attach the digital temperature sensors and contact pads of 2 mm width and 9 mm length on both ends of the stripe for contacting the conductive threads. The distance between two adjacent temperature sensors is 6 mm, to ensure that the temperature sensors on the woven e-stripes are not covered with a warp thread. Five contact areas for the temperature sensors are structured to choose the location of the sensors on the e-stripe. The substrate is then separated into 2 mm wide and 4.5 cm long stripes using a wafer saw. The digital temperature sensors are attached by flip-chip soldering.[7] The temperature sensors are encapsulated with a glob-top cover for protection. A single stripe with two temperature sensors is shown in Fig. 8.11.

Before the e-stripes are woven into the textile, two conductive threads (Bekinox VN 14/1x) are inserted into the warp beam with a distance of 3.6 cm. These two conductive threads are used to interconnect the contact pads at both ends of the e-stripes. The weaving process is then performed (Section 8.2.4) on a commercial band weaving machine of type NFREQ 42 from Müller Frick.

Figure 8.12(a) shows the woven prototype with five e-stripes in the weft direction. The conductive threads in the warp direction are not visible, because they are integrated in the textile. In Fig. 8.12(b), a schematic of the demonstrator is shown. By connecting the two conductive threads in the warp direction with an



8.12 (a) Prototype with integrated bus system. The textile contains ten digital temperature sensors (encircled white) distributed on five e-stripes. The conductive threads in warp direction serving as bus lines are not visible due to the integration. (b) Schematic of the textile integrated bus system.

appropriate measurement unit, it is possible to read out the temperature values of all 10 integrated sensors.

The ability to bend the textile was investigated using the demonstrator with the integrated temperature sensors. First, the textile was wrapped around cylindrical rods in warp and weft directions. The textile was bent to a radius of 0.75 mm without a failure of the electrical system in the textile. However, the areas of around 2 mm × 2 mm, where the digital temperature sensors are located, were locally stiff and did not bend during the experiment.

The bending rigidity of the textile was evaluated by using a Shirley Stiffness Tester (Schwartz, 2008). The influence of the integrated e-stripes compared to the same textile without e-stripes was evaluated. For the textile without integrated e-stripes, a bending rigidity G of 13.45 g cm^2/cm and for the demonstrator a bending rigidity G of 17.45 g cm^2/cm was measured. This 30% increase in the bending rigidity is accounted to the e-stripes, which are less flexible than the textile threads (Zysset *et al.*, 2010a).

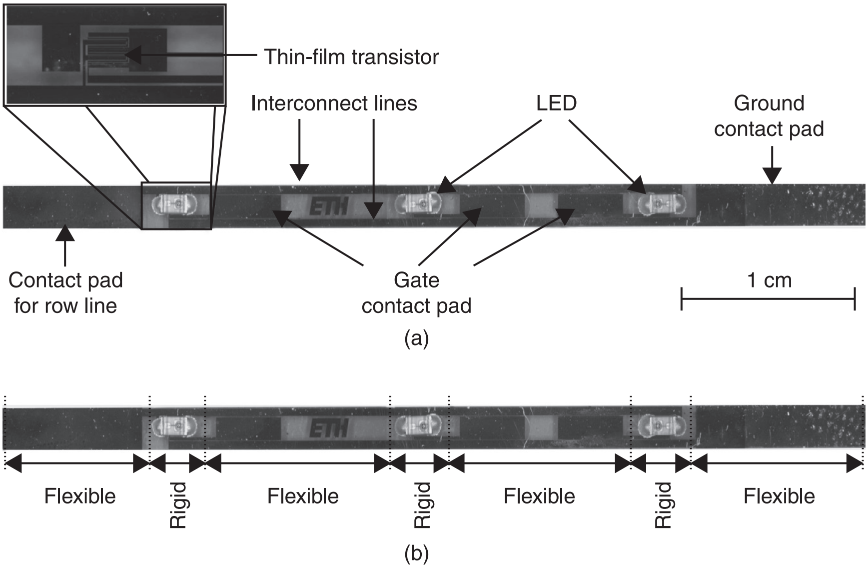
8.3.3 Textile integrated matrix

As proposed in Section 8.2.1, matrix systems integrated into woven textiles can be used to address a multitude of sensors and actuators in the textile. Therefore, a demonstrator was fabricated with three flexible stripes in the weft direction. Each e-stripe contains three SMD light emitting diodes (LEDs, type ROHM SML-311UTT86K), where each LED is controlled with a TFT, allowing turning the LED on and off. In the warp direction, three conductive threads are used to control the gates of the TFTs. With this arrangement of e-stripes and conductive threads, a 3 by 3 LED matrix with individually controllable LEDs is achieved.

In Section 8.2.3, strains of up to 12% on the material layers of woven e-stripes are reported. In comparison, TFTs based on oxide semiconductors start to crack at strains larger than 1% (Cherenack, 2010b). Oxide semiconductors for the TFTs are used, because they can be fabricated below 300 °C, which is necessary for processing on flexible substrates. In addition, oxide semiconductor TFTs provide a larger electron mobility of around $10\,cm^2V^{-1}s^{-1}$ compared to, for example, amorphous silicon TFTs ($\sim 1\,cm^2V^{-1}s^{-1}$) (Kattamis *et al.*, 2007), enabling faster switching and higher current density. To avoid cracks in the transistors, the TFTs are protected with the SMD LEDs, which are rigid and placed on top of the TFTs. This renders parts of the e-stripe rigid, which is an approach often used in flexible electronics (Graz *et al.*, 2011).

To enable the integration of TFTs as part of a textile integrated LED matrix, e-stripes are designed (Fig. 8.13(a)). On the left side of the stripe we see the power contact pad, which is used to select the row (Fig. 8.2(b)). The ground contact pad is located on the right side. From both pads, interconnect lines run along the stripe. Between the two interconnect lines, the LEDs and TFTs are located in a way that the LED fully covers the TFT and therefore provides mechanical rigidity to protect the TFT. In addition, between the two interconnect lines, the gate control pads are placed, which are later connected with the conductive threads in the warp direction. The distance between two adjacent LEDs on the e-stripe amounts to 1.5 cm; the e-stripe is 2 mm wide and 5 cm long. The LEDs have a footprint of 1.6 mm × 0.8 mm. Figure 8.13(b) indicates which parts of the e-stripe remain flexible after fabrication and which are rigid for protection of the TFTs.

The e-stripes are fabricated on a 7.6 cm × 7.6 cm Kapton E (Kapton, 2011) base substrate. First, the flexible foil is cleaned using the process described in Section 8.2.3. After cleaning, the gate contacts for the TFTs are patterned with a lift-off step: first, a photo-resist is spin-coated and patterned and 5 nm chromium and 30 nm platinum are deposited using e-beam evaporation. Then the lift-off is performed. In the next step, a 25 nm aluminum oxide (Al_2O_3) layer serving as gate dielectric is deposited at 150 °C using ALD. Next, the IGZO semiconductor is

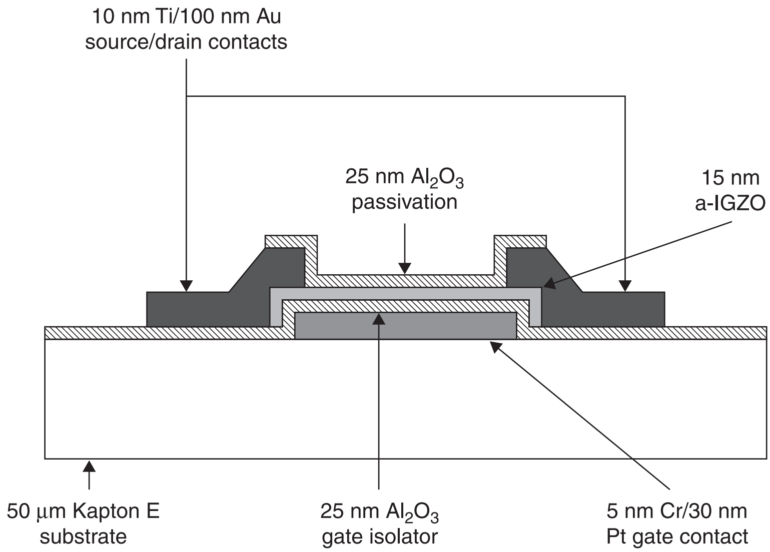


8.13 (a) Flexible stripe with contact pads for row line, ground and gate contacts of the thin-film transistors, interconnect lines and attached light-emitting diodes. The inset shows a thin-film transistor which is located beneath a light-emitting diode. (b) Indication of which parts of the stripe are flexible and which are rigid.

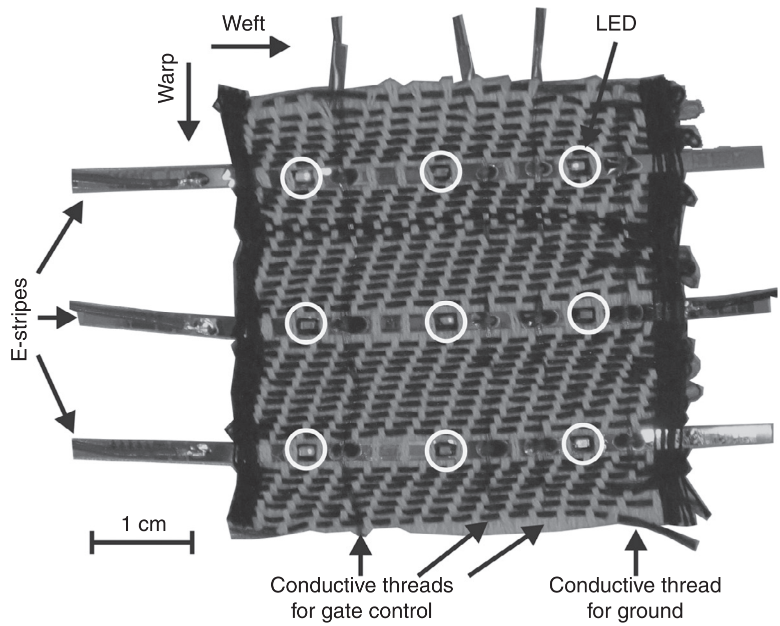
magnetron sputtered. Both layers are wet etched to form the transistor stack. The drain and source contacts, as well as the interconnect lines, the ground and supply pad and the gate contact pads, are formed using a lift-off process to structure a 10 nm titanium and 100 nm gold layer, which is e-beam evaporated. Finally, the whole stripe is covered with an insulating 25 nm Al_2O_3 layer, which is only opened at the contact pads. Figure 8.14 shows a schematic cross section of the TFT.

The e-stripes are woven on a commercial band weaving machine of type NFREQ 42 from Müller Frick, using the weaving process described in Section 8.2.4. In the warp direction, four conductive threads were integrated. Three of these conductive threads serve as column lines to control the gate contacts of the TFTs. The fourth conductive thread acts as a common ground line for all three e-stripes. Figure 8.15 shows a photo of the prototype with the integrated 3 by 3 active LED matrix, where the four LEDs in the corners and the LED at the center are turned on.

By selectively controlling (through addressing the power interconnect lines on the e-stripe and the conductive threads) each of the nine integrated LEDs, it is possible to generate patterns on the textile. This is achieved by operating the LEDs in pulsed mode with a frequency of 142 Hz, guaranteeing a continuous light signal for the human eye.



8.14 Cross section of the thin-film transistor which is used to control the LEDs.



8.15 Prototype of textile integrated active matrix. The conductive threads in warp direction for thin-film transistor gate control and ground line are not visible due to textile integration. The LEDs are encircled for better visibility.

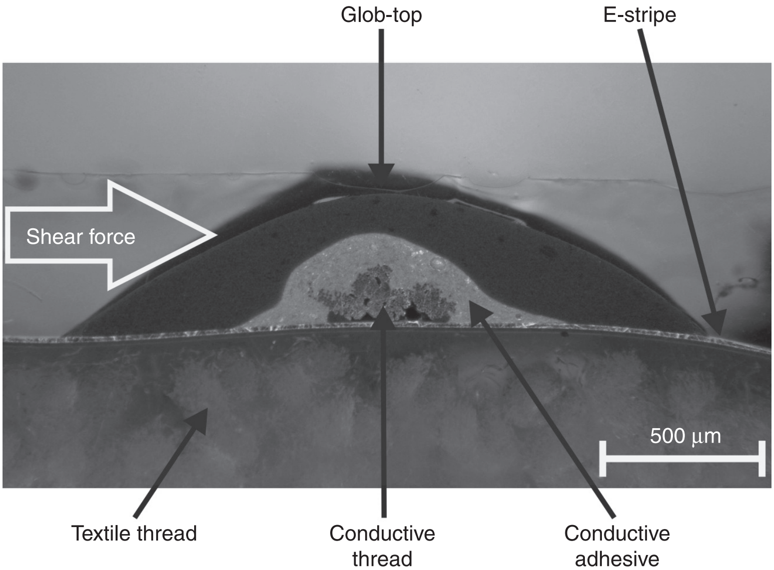
Besides being able to generate patterns through individual addressing of the LEDs, the transistor performance is investigated before and after weaving. As described in Münzenrieder *et al.* (2011), applying strain to a transistor leads to changes in the electron mobility and the switching (threshold) voltage. However, the measurements for woven TFTs protected against strain with a rigid device, indicate that the transistors are not affected by weaving. The two parameters, electron mobility and threshold voltage, remain at constant values of $9.6\,cm^2V^{-1}s^{-1}$ and 1.7 V, respectively.

8.4 Mechanical reliability of contacts

For the demonstrators shown in Sections 8.3.2 and 8.3.3, electrical contacts between conductive threads in the warp direction and contact pads on the e-stripes are crucial for establishing the desired electronic systems in woven textiles. The fabrication of the contacts with conductive adhesive and glob-top is described in Section 8.2.5. However, the destruction of such a contact can lead to partial failure of the electronics in the textile. Since potential applications of smart textiles are clothes worn by people, the smart textiles and the contacts are exposed to external forces. Therefore, the mechanical reliability of the contacts between conductive threads and contact pads on the e-stripes is investigated. Because of the shape of the contacts (they extend out of plane of the textile), they are exposed to shear forces that are exerted from objects moving, for example, a finger or a hand, over the textile surface.

Figure 8.16 shows a cross section of a contact between a conductive thread and a contact pad on a woven e-stripe. The figure shows the textile threads, the woven e-stripe and the contact to the conductive thread. In addition, the direction of the applied shear force is indicated. Maximum shear forces of 20 N were applied to the contacts and measured with a Correx force gauge. The tests were made at 20 contacts and did neither lead to detachment of the contacts nor to electrical failure of the contacts. Shear forces of 20 N are well above the 8 N of force, which a single fingertip can exert (Ledermann and Taylor, 1972). Furthermore, in a user study with seven participants, a shirt with the prototype from Section 8.3.2 integrated was worn for periods of more than 20 min and part of the time beneath a fire fighter jacket without sensor failure (Zysset *et al.*, 2010b).

However, 20 N shear forces do affect the whole system of conductive threads and e-stripes. The force applied to the contacts is transferred via the contact itself to the Kapton substrate, leading to an elongation of the e-stripe. The 20 N are equal to a stress 400 MPa, which is calculated using the cross-sectional area of the e-stripe of 2 mm × 25 μm. Using the Young's modulus of Kapton of 5.4 GPa (Kapton, 2011), the stress of 400 MPa is equal to a strain of 7.4%, which is smaller than the 12% exerted by weaving.



8.16 Cross section of a contact between a conductive thread and a contact pad on a woven e-stripe. The direction of the shear force applied to the contact is indicated by the white arrow.

8.5 Conclusion and future trends

This chapter presented an approach to fabricate smart textiles where the electronics are integrated during the weaving process. Following this approach enables the fabrication of smart textiles, which remain drapable (Section 8.3.2) compared to common approaches, where rigid parts are mounted on textile substrates. Despite the many approaches of smart-textile fabrication investigated and developed since the mid-1990s, smart textiles account for only a small percentage of the worldwide textile market (Tröster, 2011). To increase the market share of smart textiles, several challenges are faced and need to be addressed. For at least some of the challenges, the approach presented here could contribute to overcome them and turn the challenge into a potential.

The following points address several challenges, which could be addressed with regards to the smart-textile approach presented in this chapter:

- large-scale production
- washability
- user acceptance.

8.5.1 Large-scale production

Although electronics fabrication and textile fabrication are industries that can provide products at an affordable price level due to mass production, these two sectors of industry have not yet found a common ground to provide smart textiles. This is mainly due to the fact that smart textiles are not produced on a large scale but rather manually, which makes them expensive. The approach presented in Section 8.2 offers potential for scaling the technology up to smart-textile production on industrial weaving machines. In addition, electronics fabrication is based on existing processes, such as material deposition and structuring, which allow the fabrication of long e-stripes by using roll-to-roll techniques for material deposition under vacuum (Chaug *et al.*, 2004) and structuring (Noda *et al.*, 2003). Electronic devices such as ICs can be applied by automated pick-and-place packaging processes on the flexible substrates. Finally, experiments on a Dornier rapier loom have shown that it is possible to integrate long flexible stripes into woven textiles.

8.5.2 Washability

A key issue for smart textiles is washability. Early commercial smart textiles, such as the ICD+ textile coat developed by Philips and Levi (2011), required the wearer to remove all electronic components prior to washing. More recent smart-textile demonstrators, such as the Eleksen textile keyboard (Colye *et al.*, 2007), rely on waterproof packaging to protect the electronics from damage during washing.

Using flexible substrates offers potential to increase the washability of smart textiles. E-stripes with LEDs were woven into a textile and washed at 30 °C for 47 min per washing cycle. The textile was washed five times and after each cycle the LED brightness was determined. After five cycles, the e-stripes were still functional and did not show a change in LED brightness. However, increasing the washing temperature reduces the brightness and ultimately leads to failure of the device (Zysset *et al.*, 2010a).

To increase the washability, electronics on the e-stripe could be protected by sandwiching the devices between two flexible foils. Such sandwich structures were demonstrated in Kinkeldei *et al.* (2011(b)), with the purpose of reducing the strain induced by bending the electronics. In addition, improved flexible foils, which are currently investigated for organic LED fabrication with a low permeability for water and other small molecules (McCormick, 2011), could be used to protect the electronic devices.

8.5.3 User acceptance

To increase the user acceptance of smart textiles, different issues have to be addressed: in case the smart-textile measures physiological parameters, the measurements have to be reliable, the smart textiles need to be affordable, handling has to be simple to address not only technology affected people, the added electronic functionality should be integrated unobtrusively in terms of appearance and also haptic perception of the textile, etc. (Schaar and Ziefle, 2011).

Progress in electronics fabrication, in particular higher integration density of solid state electronics according to the ITRS roadmap (ITRS, 2010), the advent and majoring of new technologies such as organic electronics (Katz and Huang, 2009), printed electronics (Berggren *et al.*, 2007) and novel materials, will decrease the size of the e-stripes and increase the integration density of sensors, actuators, data processing units, etc. on the e-stripes. From all these trends in research and development, integration of electronics during the weaving process and smart-textile development in general, will benefit and offer potential to increase the user acceptance.

By overcoming the challenges of washability, large-scale production and user acceptance, smart textiles will increase their market potential. However, until smart textiles are a common item in our daily lives, they will first enter into the market of technical textiles as car or airplane interiors as well as in medical applications where monitoring of vital parameters on the human body is necessary (Tröster, 2011).

8.6 Sources of further information and advice

Further information on the topic of microelectronics fabrication and devices can be found in Sze (1982) and Menz *et al.* (2001). For thin-film electronics, Wong (2010) provides information on flexible substrates, amorphous silicon, organic materials and thin-film sensor devices. To get more information on organic electronics, Klauk (2006) addresses a multitude of topics related to materials and fabrication.

Additional material on mainly electronic aspects of smart textiles is provided by the *Proceedings of the International Symposium on Wearable Computers*, as well as the IEEE database[8] Talk2MyShirt[9] is a blog reporting on various activities in smart-textile development. The web portals ProETX[10] and SmartTextiles[11] list several companies involved in smart-textile development. On the Systex[12] web page, information on research and possible partners for smart-textile development in industry and academia are listed.

8.7 Notes

1 A printed circuit board (PCB) provides mechanical support and electrical interconnects for electronic components such as resistors, capacitors, sensors, microprocessors, etc. Structured copper layers on a non-conductive substrate connect the electronic devices, which are soldered onto the PCB.

2 Thin-film devices are made of individual layers with thicknesses, ranging from nanometers to micrometers.

[3] Roll-to-roll techniques refer to processes, where a plastic substrate or a metal foil is processed by re-reeling the substrate from one roll to a second one. During the re-reeling, material layers are deposited and structured to form electronics. For the deposition of the materials, several methods such as printing under ambient atmosphere or sputtering under vacuum are applicable.

[4] This section is based on Kinkeldei *et al.* (2011a).

[5] The formula for a RTD is $R = R_0(1 + \alpha(T - T_0))$, with R the resistance, R_0 the resistance at the known temperature T_0 and α the temperature coefficient.

[6] This section is based on Zysset *et al.* (2010a).

[7] Flip-chip bonding is a technique often used in micro-fabrication to interconnect a bare die to external circuitry with solder bumps or conductive adhesive. The solder bumps were deposited on the pads on the bare die on the top side. Similarly, the conductive adhesive is deposited onto the pads on the bare die while facing upwards. To attach the bare die to the external circuitry, it is flipped over and landed on the external circuitry. By heating up the whole system, the contacts made either of solder or conductive adhesive are established. Therefore, the process is called flip-chip bonding (Tummala, 2001).

[8] http://ieeexplore.ieee.org/Xplore/dynhome.jsp

[9] http://www.talk2myshirt.com/blog/

[10] http://www.proetex.org

[11] http://www.smarttextiles.net

[12] http://www.systex.org

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