Entry

Electronic Textiles

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Definition: Electronic textiles belong to the broader range of smart (or "intelligent") textiles. Their "smartness" is enabled by embedded or added electronics and allows the sensing of defined parameters of their environment as well as actuating according to these sensor data. For this purpose, different sensors (e.g., temperature, strain, light sensors) and actuators (e.g., LEDs or mechanical actuators) are embedded and connected with a power supply, a data processor, and internal/external communication.

1. Introduction

While textiles have been used by humans since thousands of years, smart textiles have only been developed during the last decades [1]. Usually, textiles are defined as "smart" when they can respond to changes of environmental parameters, e.g., by changing their color due to UV irradiation or by measuring vital signs and sending them to a smartphone to enable the investigation of one's fitness level. In many cases, such "smart" functionalities are based on electronic components, defining them as electronic textiles or e-textiles.

Such e-textiles usually contain sensors, actuators, internal/external communication, a power source, and finally a data processor [2]. Many of these parts were only made available during the last decades by inventions such as conductive polymers [3] or transistors, often based on one or two fine metal wires coated by an organic semiconductor [4–6]. Other parts, such as the data processor, cannot be transferred into textile structures, but due to steady miniaturization are more and more able to be integrated into textile structures [7]. Many other electronic parts made their way from being added to textiles by sewing, to integration on the fabric level and more recently even on the yarn or fiber level [8]. Nowadays, diverse levels of textile integration can be found in e-textiles, from wearable computers with openly visible electronics, using textiles only to make the electronics wearable [9,10], to fully integrated electronic functionalities [11,12].

With higher grades of integration of electronics into textiles, new challenges arise. On the one hand, textiles are flexible and often even stretchable, which causes strong mechanical influences on integrated electronics [13,14]; on the other hand, electronics which cannot be removed need to be washable [15]. Other challenges are related to the integration of batteries, power-packs, or solar cells which are usually either flexible or elastic or have a high capacity and maximum current, but normally do not combine both these properties [16–18].

Besides these technical challenges, sometimes problems occur due to high prices or due to low acceptance by the target group [19], especially when designing e-textiles measuring vital data to enable elderly people to live alone as long as possible, with the security that in case of a medical emergency the e-textile will detect the dangerous situation and call for help in time. In this situation, where an e-textile would be an ideal solution to support vulnerable people, privacy protection is of the utmost importance to increase the acceptance of the target group.

Thinking about the measurements of vital signs, such as pulse or full ECG, breathing frequency, or skin temperature, such parameters are not only important for people who may experience medical emergency situations, but also for rehabilitation and for athletes or people with physically strenuous jobs such as firefighters on duty [20–22].

In this entry, we concentrate on new technological approaches and give an overview of some recent applications of electronic textiles.

2. Technological Approaches and Recent Applications in Electronic Textiles

As mentioned above, typical parts of e-textiles are sensors, actuators, internal/external communication, a power source, and a data processor. All these parts have to be connected, either by common flexible wires or by conductive yarns or coating. The next sub-sections give a short overview of the aforementioned parts.

2.1. Conductive Yarns and Fabrics

As mentioned before, conductive polymers are highly interesting for the development of conductive yarns and fabrics. One of the most often used conductive polymers is PEDOT:PSS, which is a blend of poly(3,4-ethylenedioxythiophene) (PEDOT) with the polyelectrolyte poly(styrenesulfonate) (PSS) [23]. Coating yarns or fibers with PEDOT:PSS can result in flexible connection lines [24]. Washing, however, is still challenging and regularly improved by diverse research groups [25,26]. Ryan et al., e.g., dyed silk with PEDOT:PSS and found that core-shell structures were formed, with a PEDOT:PSS layer fully surrounding the silk cores of the fibers, with nearly unchanged resistivity during the first four washing cycles [27]. These PEDOT:PSS-dyed silk yarns could be used, e.g., to connect LEDs with a power supply (Figure 1a) or prepare a thermo-electric device (Figure 1b,c) [27].
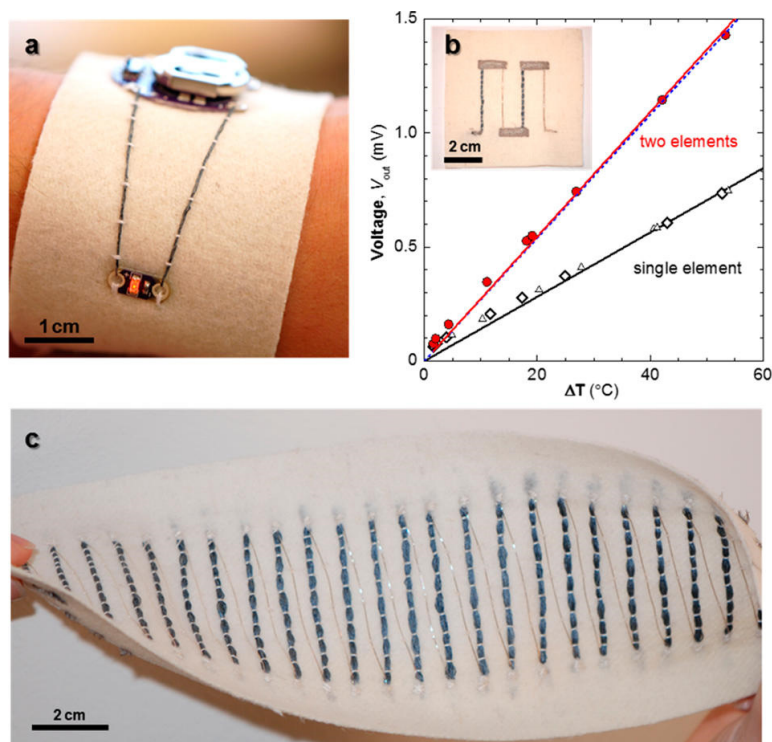

Figure 1. PEDOT:PSS-dyed silk yarns used to (**a**) contact an LED with a power supply; (**b,c**) prepare a thermoelectric device in connection with silver wires. From [27].

Other groups coated silk [28], cellulose [29], poly-paraphenylene terephthalamide [30], or cotton [31] with PEDOT:PSS, also aiming at preparing washable, abrasion resistant

conductive yarns. Besides, it is also possible to coat single fibers or nanofiber mats [32] with PEDOT:PSS as well as directly prepare PEDOT:PSS fibers by wet-spinning [33].

Besides PEDOT:PSS, other conductive polymers can be used to prepare conductive coatings or intrinsically conductive fibers. Typical other materials are polyaniline (PAni) [34,35] and polypyrrole (PPy) [36].

A much older method of embedding conductive materials into electronic textiles is the integrating of conductive metals through twisting metal wires or metal fibers into fiber yarns or metal coatings [37]. Such metal wires or fibers can be quite thin, down to approximately 1 μm, and are thus flexible enough for integration into yarns and textile fabrics [38]. Metal wires even allow for soldering or ultrasonic welding at their intersections to establish conductive fiber networks or circuits [39,40]. Finer fibers, typically from stainless steel, show high flexibility [41], but can nevertheless be destroyed by abrasion, especially during washing [42]. One of the ways to overcome this problem is through optimizing the twisting and plying of the yarn [43].

Besides these full-metal fibers and wires, there are many metal-coated polymer fiber yarns commercially available, and ongoing research aims to optimize conductivity and longevity. Gurarslan et al., e.g., prepared silver nanowires (Figure 2b) and drop-casted them onto knitted wool fabrics (Figure 2a) which were then used as pressure sensors and other capacitive sensors [44]. Coatings with silver nanoparticles can also be applied by electroless plating [45].
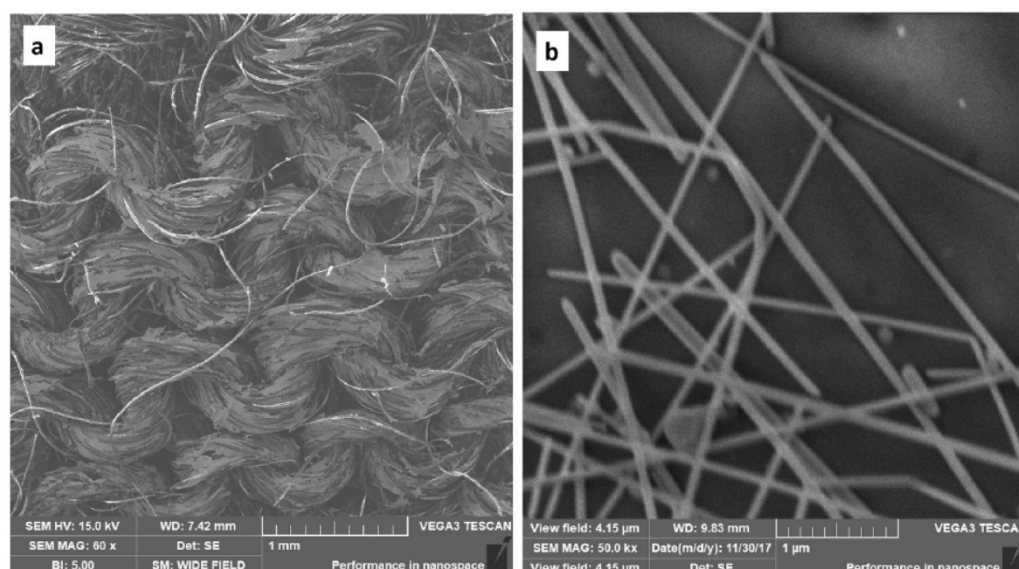

Figure 2. Scanning electron microscopy (SEM) images of (**a**) wool fabric after coating with Ag nanowires; (**b**) Ag nanowires synthesized according to the polyol method. From [44].

A gold coating was applied on a weft-knitted polyester fabric with polyurethane backing, using electroless nickel immersion gold plating, a technique which is known from printed circuit board fabrication [46]. In this way, Wu et al. could prepare a strain sensor with a high washing resistance as well as, combined with PEDOT:PSS as a front electrode and a different intermediate layer, a stretchable electroluminescent fabric [47]. Electroless plating was also used for coating cellulose or polyester fibers with Cu [48,49], while zinc was applied on stainless steel yarns by electrodeposition [50].

Generally, for most pure metal wires and full-layer metal coatings on fibers, it needs to be considered that neither wires nor metal coatings are stretchable [51]. This is why some authors suggest using a pre-stretched state for coating and the relaxed state as the "normal" state, leading to buckling of the coating [52], coil formation in only partly bonded metal coatings [53], or similar deformation which should not significantly damage the conductive

parts [54]. One such possibility is depicted in Figure 3, showing a 3D conductive network on a stretchable substrate [53].
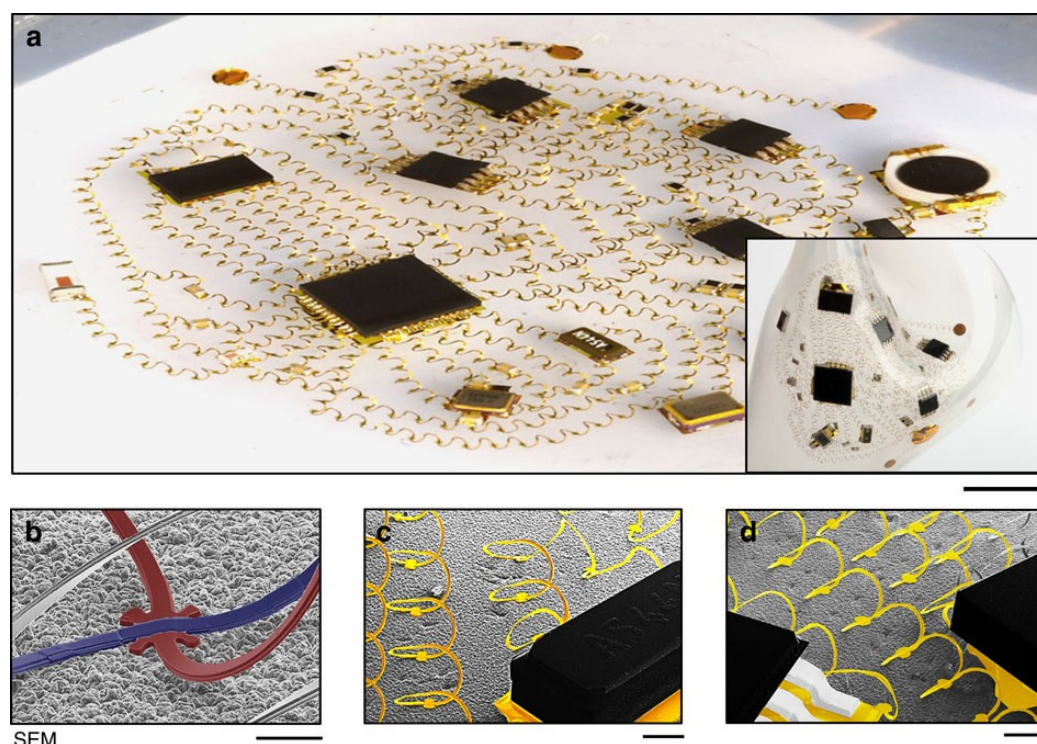

Figure 3. (**a**) Optical image of the 50% bi-axially stretched state of a 3D conductive network; scanning electron microscope images of (**b**) electrically isolated crossing points and (**c,d**) interfaces with chip parts. From [53].

Finally, another class of conductive fibers and coatings is based on different shapes of carbon. Generally, graphite, graphene, and carbon nanotubes belong to the sp^2 carbon materials, all showing (in-plane) conductivity. While graphite is a bulk (3D) material, graphene consists of exfoliated layers (2D), and carbon nanotubes can be imagined as rolled graphene layers (1D) [55].

Graphite belongs to the typical materials which are often used for textile coatings, e.g., in the form of graphite flakes which can be embedded in different binders and applied as conductive coatings on textile fabrics [56–58]. Graphene, graphene oxide (GO), and reduced graphene oxide (rGO), however, are investigated much more often [59–61]. Karim et al. reported on an up-scalable method to produce rGO-coated textiles in a continuous process [62]. rGO is, on the one hand, especially interesting since it shows good washing resistance [63]; on the other hand its conductivity is relatively low due to chemical modifications during the reduction [64] which makes it unsuitable for some applications.

Graphene coatings, on the other hand, result in a low sheet resistance, but are usually not very stable when washed. Afroi et al. developed an up-scalable method, based on microfluidization to exfoliate concentrated graphene dispersions in water, to coat textile fabrics through padding and subsequent compression rolling, before the coated textile was encapsulated by screen-printing, making it washing-resistant [65]. Cui and Zhou instead used the dip-coating of graphene and multi-wall carbon nanotubes to prepare washing-resistant coatings on cotton fabrics, which were fixed by the formation of covalent networks in the coating layer [66].

It should be mentioned that carbon black, another shape of carbon, is mostly used in combination with carbon nanofibers [67] or conductive polymers [68] to build percolation paths in spite of the small, mostly round shape of the carbon black particles, but can also be embedded in a non-conductive binder [69]. Generally, diverse combinations of

polymeric, metal, and carbon-based conductors are used for different applications, aiming at combining their respective advantages. Table 1 gives an overview of the typical sheet resistances (in Ω), linear resistances (in Ω/cm), or resistivities (in Ω cm) (depending on the geometry and measurement method, as given in the respective paper) of some of the conductive fibers and textiles described here, with clearly varying orders of magnitude depending on the desired applications.

Table 1. Resistances given in the aforementioned literature. PET: poly(ethylene terephthalate); PES: polyester.

Conductive Material	Resistivity/Sheet Resistance/Linear Resistance	Ref.
PEDOT:PSS on synthetic leather	1.6 Ω	[23]
PEDOT:PSS on PET non-woven	3.2 Ω	[23]
PEDOT:PSS-coated silk thread	0.1 Ω cm	[24]
Ag-coated silk thread	0.01 Ω cm	[24]
Ag nanowire/PEDOT:PSS-coated silk yarn	3×10^{-3} Ω cm	[28]
Ag nanowire/PEDOT:PSS-coated cellulose yarn	5.5×10^{-3} Ω cm	[29]
PEDOT:PSS-coated nanofiber mat	130 Ω	[32]
PAni/PVP electro-spun nanofiber mats	60 Ω cm	[34]
PAni/PVP electro-spun nanofiber yarn	2.4×10^3 Ω cm	[34]
PAni-coated PET yarn	80 Ω/cm	[35]
Acidified and annealed stainless steel yarn	0.7–1.8 Ω/cm	[43]
Ag nanowire-coated wool knitted fabric	2.7 Ω/cm	[44]
Ag nanoparticle-coated mercerized cotton	0.2 Ω	[45]
Electroless Cu-plated (<100 nm) membrane	3.5 Ω	[48]
Electroless Cu-plated PET 2-ply yarn	0.2 Ω/cm	[49]
Carbon nanotube-wrapped rubber fiber (strain-dependent)	26 Ω/cm–2 kΩ/cm	[52]
PAN/graphite coatings on cotton woven fabrics	400–1000 Ω/cm	[57]
Graphene oxide-coated cotton fabric	92 kΩ	[59]
Reduced graphene oxide-coated PES fabric	11 kΩ	[60]
Inkjet-printed reduced graphene oxide on cotton	2 kΩ	[61]
Silver inkjet ink printed on cotton	1.2 Ω	[61]
Graphene pad-dry-cure-coated cotton fabric	12 Ω	[65]
Drop-casted PAni/carbon black on cotton fabric	500 Ω	[68]

2.2. Textile Sensors

The aforementioned conductive materials are necessary in all e-textiles. However, diverse other materials, e.g., semiconductors, have to be added for different purposes. Usually, many materials are combined, e.g., in the form of subsequent coating layers on textile fabrics or around yarns or fibers. Here, some examples for textile-integrated sensors are described, giving an overview of which sensors can already be produced based on textile fabrics, yarns, or fibers, besides the already existing possibility of integrating small rigid sensors into fabrics or yarns.

The simplest sensors are based on pure conductive yarns or layers with different shapes and functions. Knitted fabrics with partly conductive yarns, e.g., can be used as elongation sensors and thus as breathing sensors [70], however, with the signal being superposed by a slow change of the resistance with time (the wearing out of the knitted fabric) [71]. Yarn-based elongation sensors, prepared by carbon-coated fibers wrapped around a polyester/elastic fiber core, were also found to be suitable as breathing sensors [72]. Embedding Ag nanoparticles in a stretchable fiber enabled the producing of a durable strain sensor with a large sensing range which was used in a glove to control a robot hand [73]. The integration of a strain sensor from carbon black in a thermoplastic elastomer was used to prepare a body posture registering shirt (Figure 4) [74].
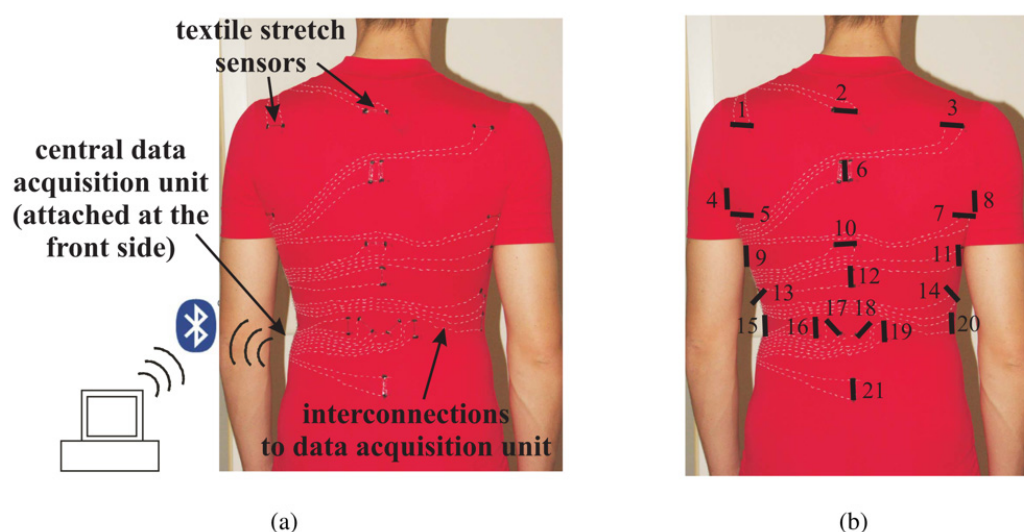
Figure 4. (**a**) Sensor threads integrated in a prototype body posture recognition shirt; (**b**) sensor positions. From [74].

Fibers coated with carbon nanotubes (CNTs) were found to be suitable temperature sensors since their resistance was nearly unchanged by the repeated bending of fibers, as opposed to conductive carbon coatings [75]. A CNT screen-printed electrode array was sandwiched between a silk fabric and a nylon fabric to form a triboelectric nanogenerator (TENG) which was found to be washable and could be used as a self-powered touch sensor or gesture sensor for human–machine interaction (HMI) [76]. ECG measurements can be performed using different conductive textiles as electrodes [77–79]. Even an NH_3 sensor was produced by a gold/CNT/gold structure, with the CNTs being coated on a cotton yarn, based on the NH_3 being a strong reducing agent and thus eliminating the majority of the holes in the CNTs, which resulted in a decrease in resistivity [80]. Polypyrrole and several other conductive polymers also respond to diverse gases in their environment and some can be made more sensitive through the chemical modification of the conductive layer [81–83].

More parameters can be detected by combining parts with different physical properties. In the simplest form, a parallel plate capacitor can be created by sandwiching a non-conductive textile or compressive foam with two conductive textiles layers, in this way preparing a pressure sensor which can, e.g., be used for gait analysis [84] or an elongation sensor usable as a breathing sensor [85]. Poly(vinylidene fluoride) (PVDF), e.g., has piezoelectric and pyroelectric properties, i.e., it responds also to temperature changes by producing an electrical charge. The latter can be used for the detection of the presence of a human [86], but has also been developed further for use in heartbeat and respiratory signal detection [87–89].

Piezoelectric materials like PVDF can generally not only be used as sensors, but can even harvest electrical energy when the piezoelectric textiles are compressed or bent [90–93].

Lactate and glucose sensors were prepared by the electrochemical deposition of platinum nanospheres on nitrogen-doped carbonized silk and the drop-casting of a lactate oxidase or glucose oxidase/chitosan solution on these Pt/silk electrodes. Sensors for Na^+ and K^+ ions were produced by adding ion selective membranes to PEDOT:PSS-coated working electrodes. Ascorbic acid and uric acid, as typical health-related biomarker molecules, were directly detected using the carbonized silk working electrode. Figure 5 depicts some of the sensor responses, showing the desired selectivity of the sensors [94].
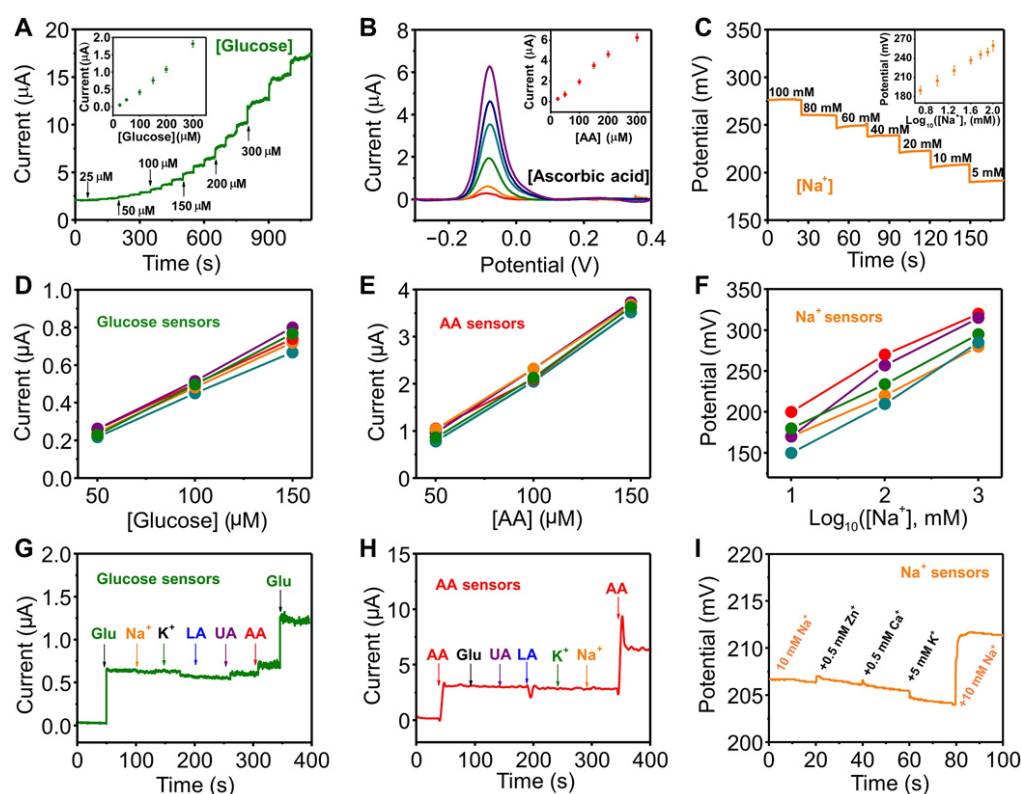
Figure 5. (**A**) Chronoamperometric response of the glucose sensor; (**B**) differential pulse voltammetry signals of the ascorbic acid sensor in ascorbic acid solution; (**C**) open circuit potential of Na^+ sensor; (**D**–**F**) reproducibility of the aforementioned sensors; (**G**–**I**) selectivity of the aforementioned sensors. From [94].

Generally, diverse physical and chemical sensors can be prepared by combining conductive materials with other materials, such as semiconductors, dielectrics, non-conductive spacers, etc. [95], as long as coating them on flexible, open-pore textile substrates is possible and the necessary materials are not toxic.

2.3. Textile Actuators

Besides LEDs, electroluminescent displays or heated conductive lines which sometimes are also regarded as actuators, actuators usually transform energy of any form into a motion [96]. One of the large fields in which textile actuators are used is soft robotics [97,98]. Many soft robotic devices contain textile fabrics, however, they work pneumatically or hydraulically, i.e., textile fabrics are only a small part of them [99–101].

Nevertheless, it is also possible to prepare actuators that are fully textile. Piezoelectric fibers or yarns, e.g., can not only be used as pressure or elongation sensors, but on the other hand can be forced to stretch or compress through the application of a voltage [37,102,103].

Shape memory polymers (SMPs) can be deformed and "remember" their original shape when an external stimulus, usually heat, is applied [104–106]. While such SMP fibers could be spun unambiguously and integrated in diverse textile fabrics, it is also possible to integrate shape memory alloys (SMAs) into fabrics. In the simplest application, such shape memory fibers can be integrated into clothes that do not need ironing [107]; in more sophisticated applications, shape memory textile composites, including woven or other textile fabrics, can be used as actuators [108–111].

Quite a simple mechanism of actuating is given by thermal expansion and contraction, similar to bi-metal stripes. Here, it must be taken into account that opposite to bi-metals, textile fabrics glued together along the whole contact area are usually less rigid and may thus show different buckling behavior as a bi-metal. Nevertheless, CNT-based actuators

especially enable large tensile stroke during heating and are thus well-suited for diverse textile applications [112].

CNTs can also be the base for elastomer actuators which are electro-thermally driven [113,114]. This means that a hybrid-coiled yarn muscle, e.g., one prepared from CNT fiber bundles coated by an elastomer-methanol composite, can be actuated by a small voltage (Figure 6) [115].
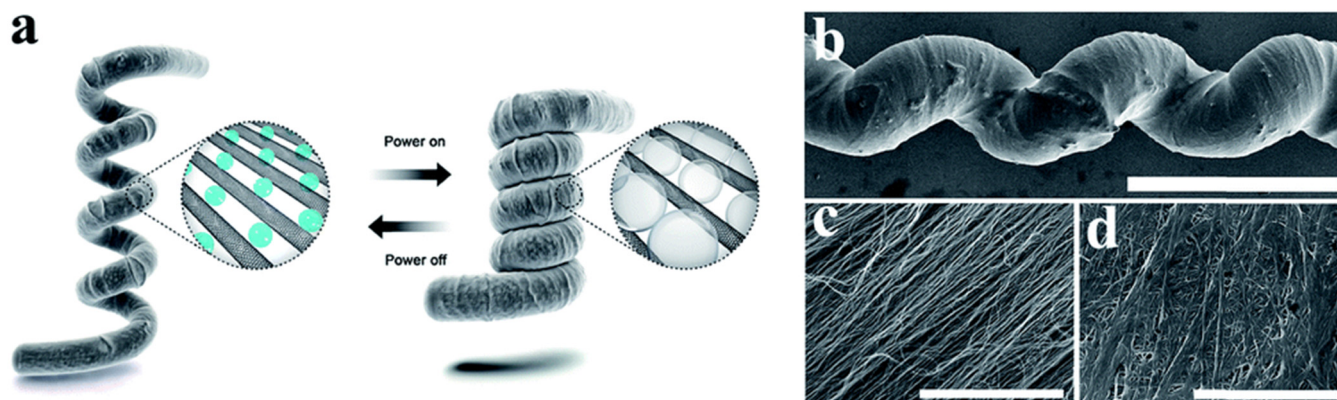

Figure 6. (**a**) The actuating mechanism of the hybrid CNT/elastomer composite; SEM images of (**b**) the composite; the surface morphology (**c**) before and (**d**) after elastomer-methanol composite infiltration of the CNTs. From [115].

Besides these examples, diverse other actuators can be integrated into textile fabrics, yarns, or fibers, stimulated by different physical or chemical parameters.

2.4. Internal and External Communication by E-Textiles

While communication inside textile fabrics mostly occurs via conductive lines, partly in the form of sophisticated textile circuits [116,117], external communication is usually performed wirelessly. Besides the radio-frequency identification (RFID) or other transmitter/receiver chips, an antenna is necessary which can be produced in a textile manner [118–120].

Hertleer et al., e.g., produced a textile antenna especially for the 2.4–2.4835 GHz bandwidth, typically used for industry, science, and medicine, by gluing a conductive fabric onto flexible foam, sandwiched between two textile layers [121].

To prepare ultra-wideband (UWB) antennae, Osman et al. embedded thin copper tape between two jean fabrics, in this way creating a bendable antenna with textile haptics [122]. Klemm and Tröster used a triple-metallized nylon fabric (Ni/Cu/Ag) on an acrylic fabric as a dielectric, connected with microstrip or coplanar feeding lines, to prepare UWB textile antennae [123]. Generally, different degrees of integration exist, from gluing the combination of patch antenna and dielectric substrate onto the clothing to directly using the clothing as a dielectric substrate (Figure 7) [124].

One of the factors that has to be considered when preparing textile antennae is their crumpling behavior [125,126]. Bai and Langley found strong deviations of the reflection coefficient when their dual-band, coplanar waveguide-fed antenna, produced by mounting a conductive fabric onto a flexible felt substrate, was crumpled to 10 mm depth, while the original length of 55 mm was reduced to 22 mm. Nevertheless, they concluded that the antenna's performance would still be acceptable for some applications [127]. Ferreira et al. produced a rectangular microstrip textile patch antenna for 2.4 GHz from copper/nickel integrated in polyester fibers with denim as the substrate. They found a decrease in the overall gain when bending the antenna and a shift of the resonance frequency to higher or lower frequencies, depending on the bending orientation [128].
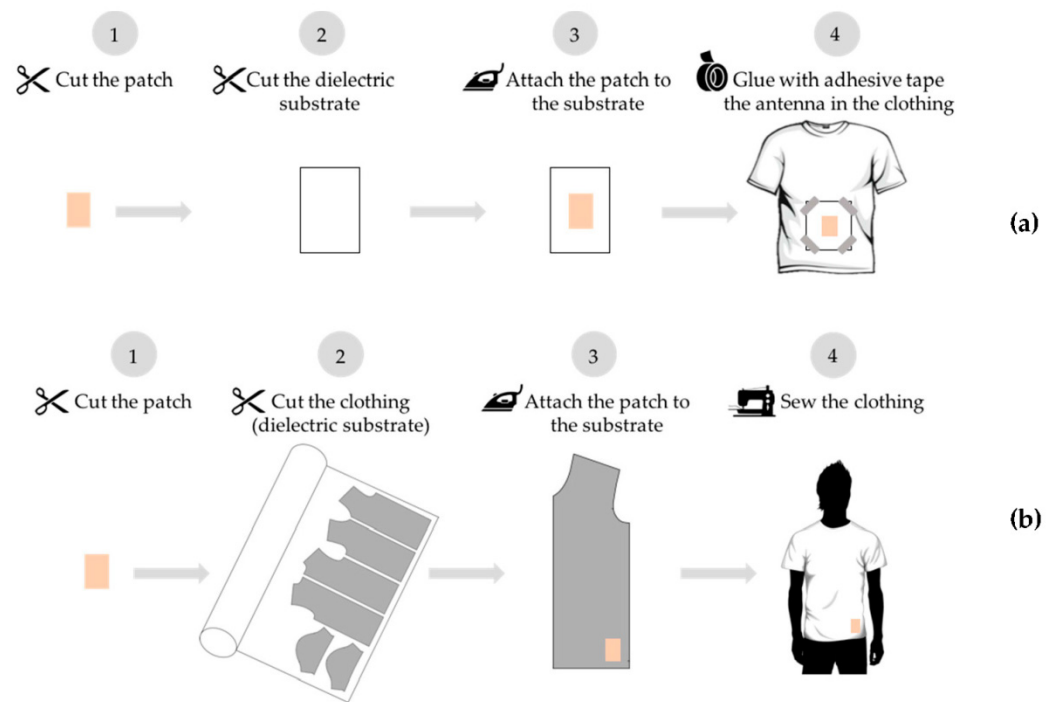
Figure 7. The integration of a patch antenna into a garment using (**a**) a separate dielectric substrate; (**b**) the clothing itself as dielectric substrate. From [124].

Another important parameter is the geometrical precision with which an antenna can be produced [129]. Kiourti et al. reported on an embroidery process, applying special conductive yarn, to reach a precision of 0.1 mm, making the accuracy similar to printed antennae or circuit boards [130].

Besides these special challenges of antennae, the common problem of washability also has to be taken into account since textile antennae, as well as textile connection lines, are not separated from the fabric before washing [131]. Scarpello et al. suggested covering the conductive screen-printed antennae on the cotton/polyester substrate with a breathable thermoplastic polyurethane (TPU) layer by ironing. In this way, not only did washing only cause small changes, but the surface roughness was also reduced, thus increasing conductivity and efficiency [132].

2.5. Textile Power Supply

Supplying power to an e-textile is one of the most complicated tasks and thus is under intense investigation by a diverse number of groups recently. Besides batteries, energy can also be stored in supercapacitors which can often be integrated into textiles more easily than batteries, since supercapacitors can be based on carbon nanotubes or composite yarn fiber electrodes, while lithium ion batteries need rigid active materials like lithium ion phosphate and graphite, and alternatives often use highly toxic organic solvents [133–135].

Recently, Yong et al. reported on a textile power module which combined a ferroelectret-based biomechanical energy harvester with a solid-state supercapacitor, both integrated into a woven cotton fabric. In their study, they reached output voltages of around 10 V and power densities of nearly 1 $\mu W/cm^{-2}$ by a compressive force of 350 N, while the supercapacitor showed a capacitance of 5.55 mF/cm^{-2} [136].

Gao et al. produced a solar cell/supercapacitor hybrid device on an activated cotton woven fabric. They prepared flower-like cobalt/aluminum-layered double hydroxide nanoarrays on cotton through a hydrothermal method to produce the positive electrode. The cotton fibers were coated with conductive graphene by dip-coating to create the negative electrode (Figure 8). Separated by a solid state electrolyte, this supercapacitor

reached a high working potential of 1.6 V, a good energy density of 55 Wh/kg, and a power density of 5.4 kW/kg [137].
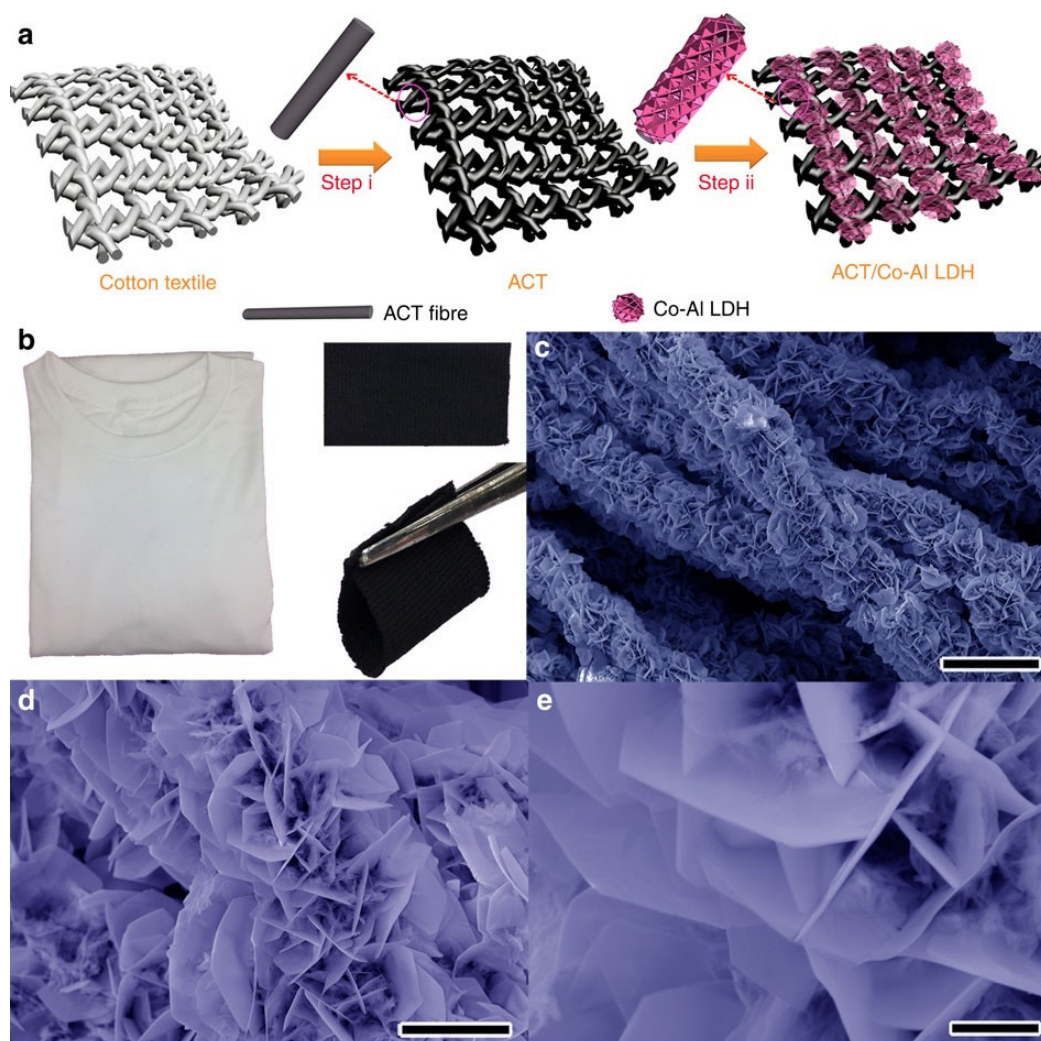

Figure 8. (**a**) Formation of the cobalt/aluminum nanostructure on the activated cotton (ACT); (**b**) cotton T-shirt; (**c**–**e**) SEM images of the cobalt/aluminum nanosheets with different magnifications (scale bars: (**c**) 20 μm, (**d**) 5 μm, and (**e**) 1 μm). From [137].

Other research concentrated on batteries, e.g., those produced by screen printing and activated by water [138], by coating $LiFePO_4$ and $Li_4Ti_5O_{12}$ on a Ni-coated woven polyester fabric as the cathode and the anode, respectively [139], or by producing lithium-sulfur batteries on activated cotton textiles coated with rGO [140].

As these few examples already show, there is a broad range of physical principles used for energy storage, including batteries, supercapacitors, and pseudo-capacitors [141–143], based on different electrochemical processes. The research area of textile power supplies in particular necessitates strongly interdisciplinary research to enable the combining of new ideas from a physical/chemical point of view with the textile engineering necessary for realization.

2.6. Data Processing in Textiles

Data processing, as mentioned before, cannot be transferred into textile structures, but necessitates that pure or single-board microcontrollers are embedded in textile fabrics or attached onto them [7]. While single transistors can nowadays be produced based on textile fabrics and used for transistor-based sensors [144–146], transferring a full microcontroller

into textile form is at the current state of technology unimaginable. Hence, this part of the e-textiles will most probably remain as the last non-textile element for a long time.

2.7. Methods to Apply Conductive and Other Layers on Textile Fabrics, Yarns and Fibers

Besides coating processes which use typical textile technologies, such as coating with a doctor blade or dip-coating [66,137], other methods used to apply conductive and other layers are screen-printing [65,76,132,138] or inkjet printing [61,69].

Other methods include vapor-processing techniques, such as chemical vapor deposition [147–149] or atomic layer deposition [150–152]. With these methods, very fine and thus typically very flexible layers can be deposited on textile fabrics or around fibers.

3. Conclusions and Prospects

Electronic textiles can be used for a broad range of applications, from health monitoring and monitoring the vital signs of athletes to soft robotics, and from gas sensors to piezoresistive sensors monitoring windmill blades. Generally, since we as humans are normally surrounded by textiles, most applications of e-textiles are related to humans, supporting us in different situations, making the use of electronic devices easier by integrating them fully or partly into garments or just adding new functionalities due to design aspects.

It should not be forgotten that the deeper electronic functions are integrated into textiles the more challenging the development is, since experience from rigid electronics can only partly be transferred. Nevertheless, the research and development of electronic textiles are steadily advancing so that new functionalities can regularly be expected to become available, making electronic textiles more and more useful in our daily lives.

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