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Textile Electronics – Prospects, Advances, Challenges and Opportunities

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ABSTRACT

The field of textile electronics aims to use clothing materials and fabrics as an active or activated substrate for electronics. This is an intriguing idea for researchers, however, the field comes with its own challenges and design requirements. A textile electronic system should be functional, reliable, safe and affordable while maintaining the original utility of the fabric. This review paper presents a comprehensive picture of prospects, advances, challenges and opportunities of textile electronics. It also offers a critical outlook to advance the field for technology translation.

INTRODUCTION

Textiles have been a necessary accessory in our daily life for thousands of years. They are physically flexible and stretchable. Therefore, with the emergence and growth of flexible and stretchable electronics, it is expected that textiles will serve as the natural application venue for such electronics. However, that is not the case as durability, affordability and mass manufacturability are critical requirements to achieve integration of electronics into textiles. From that perspective, textile electronics has remained an illusory technological challenge. To address this challenge, innovative works have been reported focusing on functionalization of textiles to serve as an activated electronic material, interconnects formation from activated conductive textiles, and integration of sensors and energy modules. In order to improve the field of textile electronics we need to collectively establish guidelines of methods, materials and designs. Firstly, we need to analyze full systems in terms of functionality, durability, reliability, convenience, affordability portability and mass manufacturability. Next, an overall electronic system is not a single device – therefore, we need a systematic categorical review comparing different designs, fabrication methods and the effect of the material used is needed. Finally, we need to understand activation methods and active material synthesis. Here, we provide an unbiased comprehensive review focusing on the aforementioned points. This review paper is segmented into several sections; Design Criteria details a variety of design metrics; Progress and Advances discusses recent advances made in materials, fabrication and devices; Challenges and Future Outlook chronicles the remaining challenges, potential strategies to address them and future outlook; finally, Conclusion section summarizes the essence of the paper.

DESIGN CRITERIA

This work will look into textile electronics from several perspectives: a functional garment integrated system, devices and electronics used, fabrication of active textile and activation methods of commercial textiles. Each level of the system has their own requirements that varies with applications, however, there are certain guidelines. Like the clothes we wear in our daily life, a functional garment should be comfortable, breathable and suitable for the intended weather and environmental conditions. For example, sports-wear should be sweat wicking and provide evaporative cooling. Diversely, firefighters' uniforms should protect them from heat and other occupational dangers. An electronic garment should also be affordable while considering the system’s complexity and purpose. Using already available commercial garments and integrating the electronics into them preserves the functionality of the clothing and could curb costs co. The methods of electronics fabrication and integration should be direct, inexpensive and repeatable on a large scale.

The weight of an electronic garment should not exceed the weight of the equivalent normal garment it replaces. The system should be biocompatible and non-toxic. Electronic garments should be tested to confirm lack of irritation or allergy to the user. The system might need signal processing and decision-making units or a method to communicate the outputs and results to an accessible system. The user should also be able to choose the privacy settings of their systems. For example, a patient would limit disclosure of information to a doctor. The system should be reusable and washable, using regular washing methods like hand washing and washing machine. The usage and washing should not affect its functionality. The system should either be rechargeable by the user or have a self-charging device. The power supply and storage should be efficient for the application requirements. For safety, the current and voltage exposure to the user should consider protecting the user from shocks. Table I is a summary of the important considerations of textile electronics system.

When it comes to the devices and sensors used, each one will have certain criteria based on the electrical performance. Their electrical properties should be comparable to the devices made of solid-state substrates. Their physical properties, however, should be comparable to textiles. For example, the devices should be flexible, stretchable and light weight. This should be achieved without compromising the function even as some mechanical stress is applied on the device due to the movement of the user.

Generally, when we have more than one sensor or device, there should be no signal interference between the devices integrated in the garment and no compensation of the electronics functionality due to integration. The devices should be protected from environmental conditions and surroundings like temperature, humidity and dust so the functionality is not compromised.

Looking at fabrics and fibers that serve as substrate material, they should be comfortable, stretchable when needed and non-toxic. If they are synthesized textiles, they should have good and suitable intrinsic qualities. For example, conductive material used should have resistivity of 17.2 nΩm and the insulator material should have 1.5 x 1014 Ωm. When semiconductor materials are used, they should have a resistivity between 10-5 and 103. The material should not degrade or oxidize with usage and washing. Activation and weaving/sewing methods are diverse, but they should be inexpensive and reproducible. Some methods depend on printing or coating the fabric with certain activation material, these methods might be straight forward but there is a compromise for accuracy and interface quality. On the other hand, chemical treatment and deposition produce better quality of the material but they usually require expensive or long methods.

Table I. electronic garment considerations by category

Environment Application	User Interaction	Reliability	Electronic Functions
Water Resistant or Water Proof	Non-Toxic	Re-usable	Power- on-board or off-board charging
UV Blocking	Non-Irritating	Washable	Energy Harvesting
Heat Guard (ex: fireman suit)	Biocompatible	Device to Device Interference	Device to Device Interference
Cooling	Electric shock guard	Stretchable/Flexible	Method of Data Transfer
Sweat Wicking	Weight Appropriate	-	On-board or Off-board Data Analysis
Stretchable	Control of Privacy Settings	-	-
Flexible	End of Use Disposal	-	-

PROGRESS AND ADVANCES

In this section, recent advances in research are reviewed and organized into six sub-sections based on function. Each device or system is evaluated based on the design criteria mentioned in the previous section. The first section will look into physiological monitoring systems. The second section includes review of individual sensors. Advances in other functional parts such as lighting and RFID are discussed in section three. Section four is dedicated to field effect transistors (FETs). Energy storage and harvesting is reviewed in section five. Lastly, we review some of the recent methods used to form interconnects, activate textile materials and syntheses of activated fibers and fabrics.

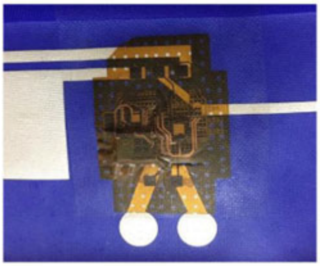
Complete Systems

A basic method to realize textile electronics is to integrate already existing sensors, batteries, and components into garments. In 2006, a study made by Edmison *et al.* looks into design issues faced while integrating sensors into textile and then provides a system that solves these issues. They prototyped a physiology monitoring pair of pants that contain an accelerometer, piezoelectric films, wireless receiver for the heart rate monitor and environmental temperature sensor. The accelerometer was placed on the ankle and the piezoelectric film on the knee. The heart rate sensor was attached on a chest strap and connected to a wireless receiver located at the hip along with a temperature sensor. These devices were connected to a printed circuit board (PCB) attached to the fabric and the connecting wires were woven into the garment. [1]. The integration method used here is simple using commercially available devices and making it a successful early demonstration prototype. However, we don't have enough information to evaluate the accuracy and functionality of the system. It was mentioned that there is a battery pack, but we do not have information about the battery's life time. Aside from that, the memory could not collect data for more than 12 minutes, which is not sufficient. Also, we do not have an explanation or characterization of comfortability or wash ability.

In 2010, another group demonstrated garment integration of existing electronics in civil protection and firefighter uniforms. It contained multiple sensors to provide real time monitoring of physiological and environmental parameters related to occupational needs. The sensors were attached in 3 places: inner garment, outer garment and boots. The inner garment was elastic and contained several electrodes knitted and sewn on the garment for sensing heart rate. The inner garment included: Two strain sensors used to capture fabric deformation due to chest movement, digital body temperature sensor and an optical transistor based on a controlled source of electromagnetic signals to measure Oxygen saturation. On the outer garment, a waterproof environmental temperature sensor was sewn. The other devices located on the outer garment were detachable and included commercial Lithium batteries, GPS module and motion sensor. A CO sensor was placed close to the mouth and nose protected by a waterproof gas permeable membrane. Finally, the CO_2 sensor, which has improved sensing closer to the ground, was placed on the boots. [2]. This group presented a textile electronic system directed towards a specific application. The clothes maintained the properties of the regular emergency operators' garments like price, availability and protection, while adding the benefits of the integrated electronic system to aid the workers' safety and performance. However, the commercially available devices are not specifically designed for textile applications and are not ideally suitable due to weight, rigidity and size.

A paper by Hsu *et al.* presents a physiological monitoring system that communicates respiration, heart rate, ECG, movement and temperature. This work utilized standard screen printing methods to create thin and non-irritating electrodes. The electrodes were printed using a low temperature process with conductive ink. A monitoring controller flexible PCB (FPCB) was embedded on the fabric and covered with plastic hard-shell for protection from dust and water. The electrodes were then combined by heat pressing and glue lamination as shown in figure 1 [3]. The method is simple and direct. It also has the advantage of including a flexible PCB protected from water and dust. The characterization results are not enough to evaluate the performance.

(a) screen printed electrodes



(b) FPCB layer

Figure 1. Flexible PCB (FPCB) and conductive ink patterns layout for physiological monitoring system. Reprinted with permission from [3].

Paradiso et al. developed a system named WEALTHY to simultaneously measure several body vitals like respiration electrocardiogram, activity and temperature. Conductive fabric electrodes were made with two stainless steel wires twisted around viscose yarn. The electrodes were then knitted by using tubular intarsia technique to get conductive/insulator fabric. A hydrogel membrane was used to enhance the electrical signal quality due to the presence of ion in membrane that improves the flow of charges. The second part of the system was a piezo resistive fabric sensor that contained Lycra fabric coated with carbon loaded rubber and commercial electroconductive yarn knitted on the multifunctional fabric. The coated Lycra was used to measure respiration signals and the yarn was used as an activity sensor. To evaluate the performance, the fabricated electrodes were compared to commercial electrodes and the data is reported [4]. The electrodes fabricated have demonstrated measurements comparable with standard electrodes (figure 2 and figure 3)

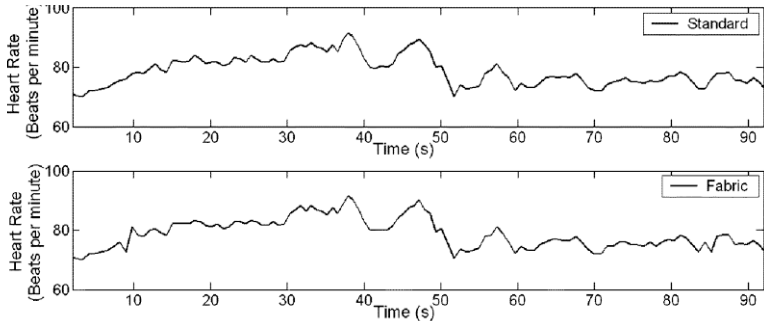


Figure 2. Heart rate obtained from WEALTHY compared with heart rate measured by standard electrodes. Reprinted with permission from [4].

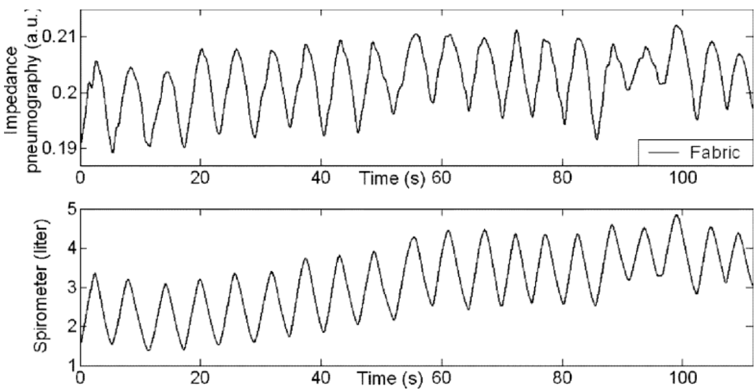


Figure 3. Respiration signal obtained from WEALTHY compared with respiration measured by standard electrodes. Reprinted with permission from [4].

Textile, Flexible Passive Sensors

This subsection will discuss sensors that could be used for various applications. Humidity sensors could be used to monitor breathing or environmental conditions. Strain and piezoelectric sensors could also measure physiological signals or be used for communication and user interface. Humidity sensors can be capacitive or resistive based. Capacitive sensing has better sensitivity than resistive due to its ability to detect airborne particles. The group at, developed a flexible thin, cylindrical sensor that could be easily embedded into textile material like a nose/mouth mask to measure humidity in exhaled air. The yarn chosen was a special type normally used in sportswear due to its high moisture retention ability. It also has a relatively high specific area due to the designed cross-section, which made it suitable as the capacitor dielectric layer. The permittivity of the yarn increased with water absorption and thus the capacitance change was an indication of the humidity or water content in the air. The yarn was combined with two copper wires to form a biaxial sheathe structure to form Clean Cool shaped sensor

(CCYS) shown in figure 4. Different humidity response, resistivity, repeatability responsiveness, reversibility and hysteresis tests were performed. The device was then applied to a mask to detect breathing activity. The results are shown in figure 5 [5]. This work is unique due to the ability of detecting breath using humidity whereas most breathing monitoring devices use strain sensor.

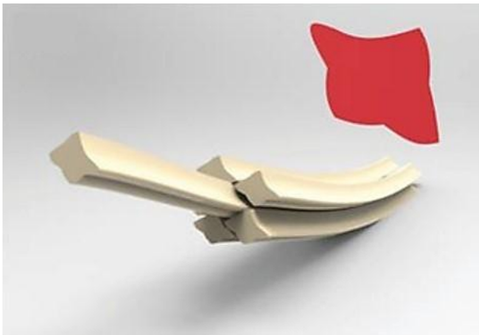


Figure 4. The CCYS yarn shape. Reprinted with permission from [5].

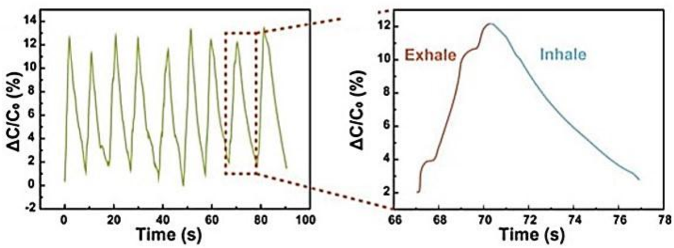


Figure 5. Detected breathing activity of the CCYS. Reprinted with permission from [5].

The next paper focused on two different fabrication methods for capacitive humidity sensor. The first sensor was fully printed and consists of electrodes, isolation and dielectric layers. The electrodes were made by printing a carbon containing paste on polyester fabric. Both the isolation and dielectric layers were fabricated by knife coating. The isolation layers contained both polyurethane layer and sol gel trimethoxy(octyl)silane layers and the dielectric layer was tetraethyl orthosilicate sol. The second sensor was spun and embroidered. The core filament was a thick copper wire surrounded by viscous staple fibers. Two core-sheath yarns were wrapped around each other and attached with an additional thread system to be woven on textile polyester [6]. The paper presents results on changes in capacitance, the maximum capacitance this device reached was around 1500 pf while the previous sensor could reach the capacitance of 7000 pf. However, the capacitance range is not an indication of accuracy and we do not have enough data to make this comparison.

Lee *et al.* reported fabrication of a fiber strain sensor and demonstrated two possible applications. The fibers used were polyurethane based commercialized stretchable fibers. They were immersed into 40 wt % $AgCF_3COO$ solution in ethanol. Trifluoroacetate anions (CF_3COO-) induced an ion-dipole interaction with the hydroxyl group –OH of the solvent which was easily absorbed by the fibers. A solution of hydrazine hydrate $N_2H_4.4H_2O$ was used to convert the Ag precursor to Ag nanoparticles. Ag rich shell formed along the surface of the fiber and it cracked when a strain was first applied to the fiber, forming two regions of exposed thread and Ag coated thread (figure 6). The sensor was tested in two different application scenarios. They imbedded the sensor on each finger of a glove and were able to monitor the movement as the fingers of the glove were moved (figure 7). They also tested the sensor with an artificial bladder for monitoring expansion of the bladder as it was filled (figure 8) [7,8]. This device shows good performance and a large range of applications like physiological monitoring and user interface applications.

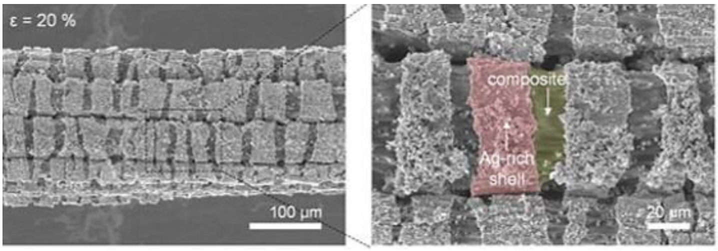


Figure 6. SEM image of the strain sensor and its regions. Reprinted with permission from [7,8].

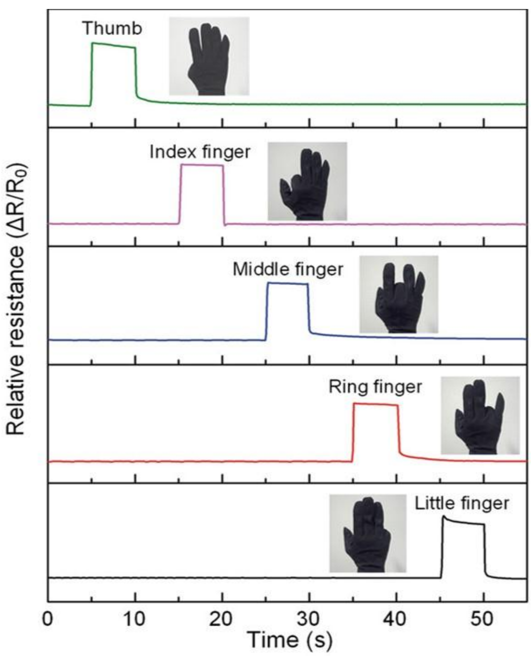


Figure 7. Test results of fiber strain sensor applied on glove. Reprinted with permission from [7,8].

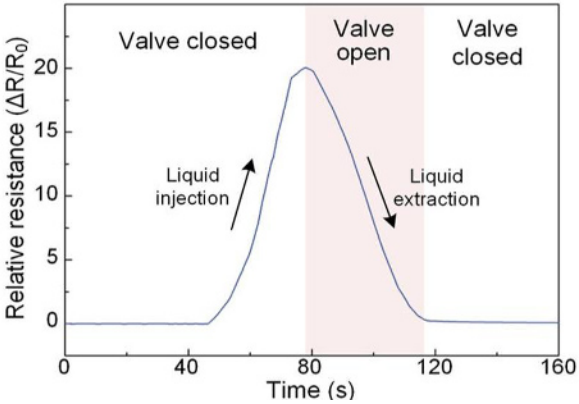


Figure 8. Measurements from fiber strain sensors embedded in artificial bladder. Reprinted with permission from [7,8].

The last two systems presented in this section have possible applications as user interface, sensing inputs that could be translated to actions. The first system is named Grabic, which is a sensor that utilizes the ability of fabric to fold to generate input signals and activate the device. This device had two parts: a microcontroller that was not flexible and a sensor that contained 30 pads of conductive thread. The thread used was commercially available conductive thread and the lines leading from the pads to the landing zone was insulated by stitching over them with non-conductive thread. The final structure allowed the user to slide the sensor in all directions without the filaments hanging onto each other. The user pinched the fold on the sensor and the pads came into contact with each other, which was sensed by the microcontroller [9]. The device is not intuitive to use, its applications are not clear, and the sensor does not detect small movements.

The second system is a stretchable keyboard based on conductive polymer electrodes. The electrodes were printed with poly (3,4-ethylenedioxythiophene) polystyrene sulfonate PEDOT: PSS on knitted textile. To test the effectiveness of PEDOT: PSS in this concept, a small textile piece was coated then stretched up to 30%, the resistance change was negligible. Even after 1000 cycles of 20% applied strain the change in resistance is only about 10%. Polydimethylsiloxane (PDMS) coating was applied as an insulating layer. The force applied by the finger press changed the capacitance of the sensor and therefore an input was detected. The final system is PEDOT/PDMS/Counter electrode structure, where the counter electrode is the human finger. A keyboard of 10 numbered nodes was tested to show a change in capacitance when a certain node was pressed as shown in figure 9 [10]. The fabrication methods are very simple which reduces the cost. The operation method is based on simple logic and cannot be used to perform hard tasks.

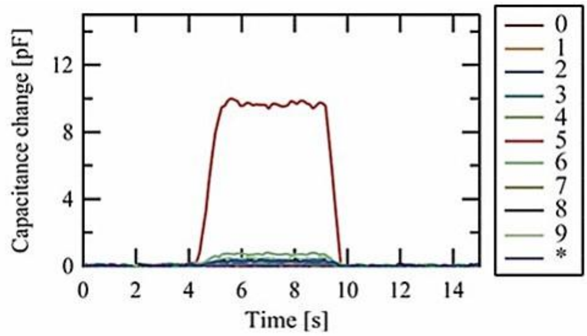


Figure 9. Capacitance change when node 5 is pressed. Reprinted with permission from [10].

Active Components

Heretofore the reviewed research devices have been devices or systems based on sensors. This subsection will present research in other flexible and textile electronics. A flexible lighting film that could be combined with textile is designed by Huang *et al.* The structure had four layers that included substrate, printing circle, flexible/stretchable conductive plastic and lightning device. The printing circle was made with printed ink in textile, the conductive plastic was used to mount the LED system onto the fabric. The LED system could be used in a variety of applications. An example presented was connecting it to a physiological signal monitor like heart rate, so it would provide a visible indication of the body status [11]. This method could be used for simple light indications but cannot be used to indicate important information (like the value of heart rate). However, the fabrication is inexpensive and fast.

Another group presented a textile radio frequency identification (RFID) tag made with textile electronics. Textile microstrip antenna was woven with 3 sets of yarn, wrap, weft and z yarns. This is stronger and better than a stack of 2D material. The operation frequency was designed at 1.8 GHz and was constrained by the weaving machine used for fabrication. Dual polarized antenna has the property of sending and receiving signals at the same time which fits for high sensitivity RFIS antennas. The tag contained two ports named port one and two, located on the center of two sides of the top square surface. They were connected to a radiation patch located in the middle square and then a ground platform. These were all made with copper yarn. The 3D structure was made of weaved E-glass yarn. Finally, 50-ohm coaxial connectors were soldered at the two ports of the antenna (figure 10). When it comes to the isolation of the antenna, the results showed that 90% of the signal power transmitted from port 1 would not be received by port 2 which means small signal interference between the two ports (figure 11) [12]. The device showed accurate results for transmitting at a specific frequency, however, designs or tests for other frequencies were not presented.

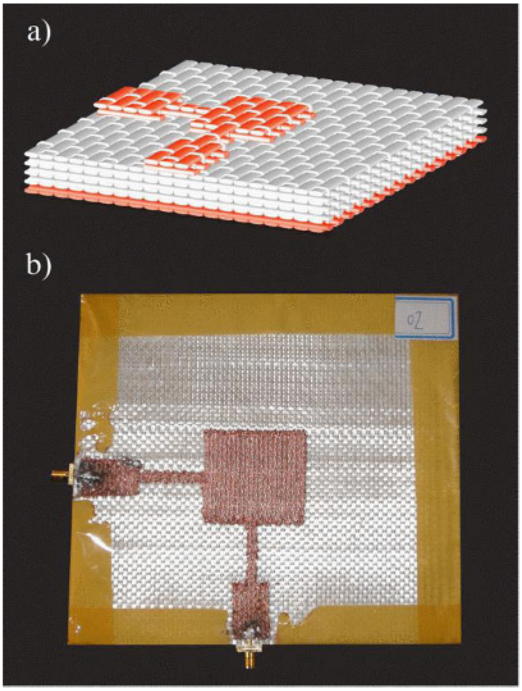


Figure 10. Dual polarized antenna design. Reprinted with permission from [12].

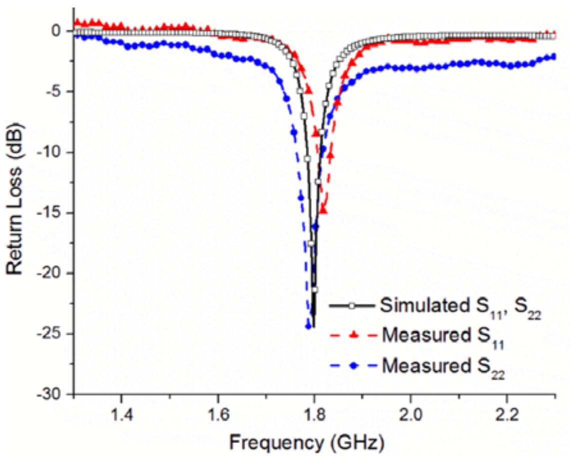


Figure 11. Simulated and measured return loss. Reprinted with permission from [12].

A novel textile absorber was proposed by Lee *et al.* for wearable applications fabricated by screen printing technology on ordinary textiles. Metamaterial (MM) absorbers consist of infinitely periodic unit cell structure and hence can be easily expanded to the required space and it can be implemented on a thin substrate, as compared to conventional electromagnetic wave absorption materials. The Chanel logo was printed using conductive silver ink on the top layer. When an electromagnetic wave is incident on the absorber the transmission will be stopped by the bottom layer which is entirely covered with copper. A prototype sheet MM absorber that has the size of 24.5 x 24.5 mm was fabricated by printing 35x35 repeated unit cell. The absorption was simulated and also measured, and we can see from figure 12 that the two correspond almost perfectly at 10.8 GHz, however the bandwidth of measured is broader than simulation [13]. The applications of this tool or customizability methods are not discussed in the paper however possible applications for MM absorbers in textiles include camouflage clothing or photovoltaic energy harvesting on clothing using existing logo placement.

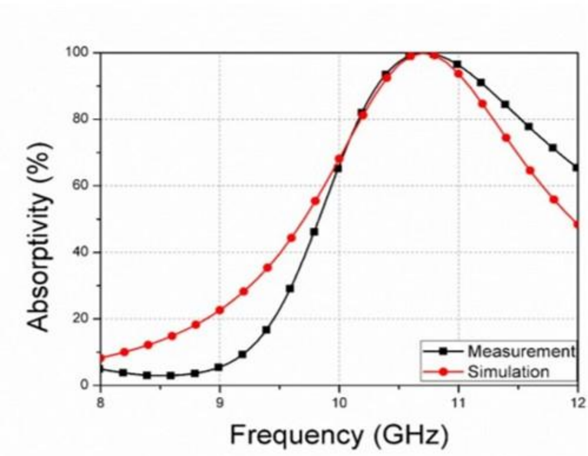


Figure 12. Simulated and measured absorption. Reprinted with permission from [13].

Field effect transistors (FETs) are essential components in any electronics system. This section will present some of the recent work to demonstrate them on textile substrate. Our comments are included at the end of the section after all devices are presented.

The first uses woven polyethylene terephthalate (PET) textile as bottom gate contact structure. Buffering layer made of polydimethylsiloxane (PDMS) was used to facilitate the fabrication on the textile. The gate electrode was made with thermally evaporated chromium/gold deposition. PDMS was used as gate dielectric due to its intrinsic elasticity and high mechanical strength. The source and drain electrodes were made with deposited gold. The organic nanofibers used as the semiconductor material were fabricated by electrospinning poly (3,3‴-didodecylquarterthiophene) (PQT-12) and poly (ethylene oxide) (PEO) to make PQT-12: PEO [14]. The field effect mobility of PQT-12:PEO is lower than that of solid-state devices due to the increased trap sites. However, even during bending measurement, the devices showed relatively stable performance with bending radius of 0.75 mm [14]. Figure 13 shows electrical performance of the OFET.

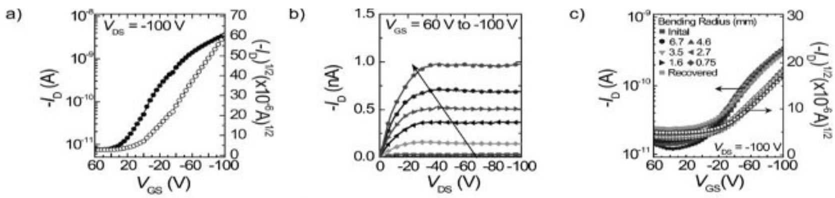


Figure 13. Measurements obtained with PET based organic field effect transistor (OFET). Reprinted with permission from [14].

Another OFET is reported by a different group and was based on Poly (3-hexylthiophene-2,5-diyl) (P3HT) and imidazolium ionic liquid. Bottom contact organic thin film transistor was fabricated at fiber junctions and it was able to operate in both field effect and electrochemical operation modes. Micro-gaps were created in thin film conducting material on top of fiber monofilaments. Then, they were coated with semiconductor conjugated polymer to form a second layer. The electrolyte gated OTFT were formed by depositing solid phase electrolyte at the fiber junctions. The source and drain micro-gaps were weaved like a fiber mesh where the upper fibers were used as shadow masks for patterning the lower layer of the fiber. A gold layer was evaporated through these masks onto the lower fiber. Thin film purified regulator P3HT were formed around the gold-coated fibers by pulling these out of a solution at relatively constant speed to allow formation of thin films (figure 14). The I-V characterization results of the device are reported [15].

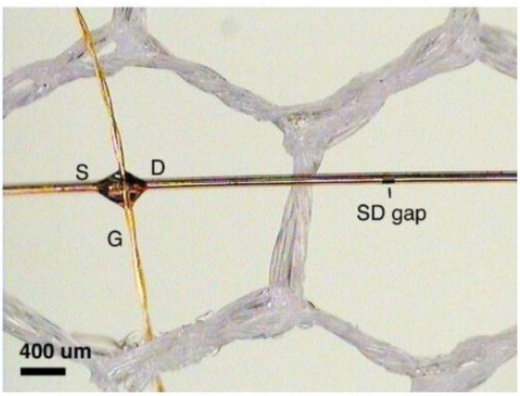


Figure 14. A close-up image showing fiber transistor. Reprinted with permission from [15].

The next device is an organic electrochemical transistor (OECT) array on fabric. Nylon nanofilament fibers were used as a substrate and coated with PEDOT-Cl with reactive vapor deposition. The fibers coated with highly doped polymer were used to stitch a parallel chemical transistor on silk backing fabric. The geometry of the device could have been customized by controlling the stitching style and density. For example, the channel geometry influences the gate voltage and the gate/channel volume ratio affects the transfer characteristics. Figure 15 shows the schematics and output I-V characteristics for an OECT using PEDOT-Cl as channel material [16].

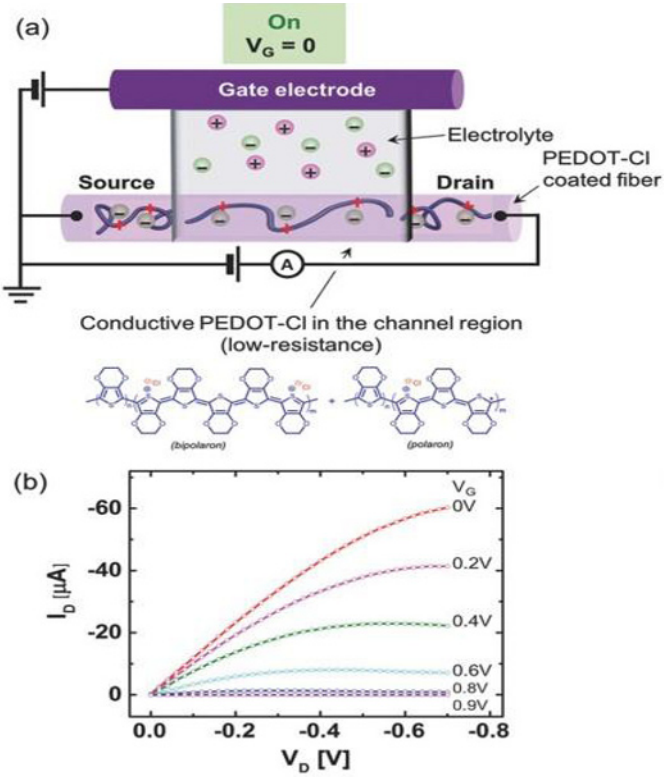


Figure 15. OECT I-V characteristics and schematics. Reprinted with permission from [16].

It is difficult to compare different FET devices in terms of electrical properties when they are different in design, fabrication methods, material and purpose. Since this area of FETs on textile is still new, device performance would need to be analyzed based on the application requirements. The previously mentioned OFET and OECT devices showed complicated processes, which is expected for making a device with this complexity. They displayed good performance compared to organic flexible solid-state devices. They are also biocompatible and safe for human skin.

Energy Harvesting and storage

In an effort to create self-reliant stand-alone textile integrated systems, power needs to be considered. Research is focused on energy harvesting as well as energy storage devices. Recent developments in textile electronics will be reviewed in this section.

A thermoelectric device was fabricated using textile materials. Two rectangles of poly(3,4-ethylenedioxythiophene) doped with chloride (PEDOT-Cl) formed the textile thermopile on tobacco cotton and was connected with carbon fiber thread. Thermo-voltage output when worn on hand was 23 mV (constant) [17]. Figure 16 shows the power and voltage output of the device with temperature change. Although the continuity of the voltage provided is important, the voltage is not sufficient to power a whole system unless a large number are combined. Also, we do not have data to compare these devices to solid state devices fabricated with the same methods.

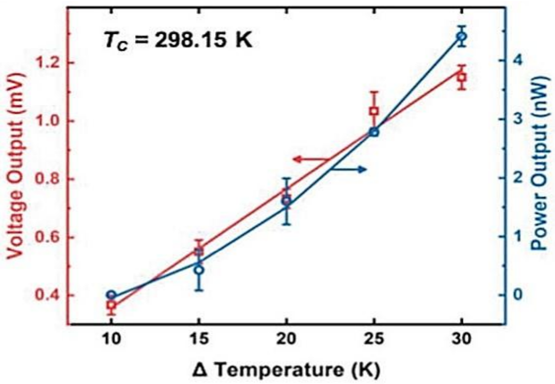


Figure 16. The output power and voltage of thermoelectric generator. Reprinted with permission from [17].

Another energy harvesting device used Microbial Fuel Cells – made out of biodegradable and organic material and uses microbes on human fluids to generate electricity. The demonstrated devices overcame obstacles faced in traditional MFCs by reducing fabrication time, cost and removing the wax-based membrane between anode and cathode which reduced the internal resistance and avoids undesirable pH gradient. On a textile substrate, printed ethylene-glycol (RG) modified PEDOT PSS was used to form conductive anodic chamber. Then, 3-glycidoxypropu-trimethoxysilane (3G) was introduced to improve the hydrophilic properties. PEDOT-PSS modified silver oxide paste was printed on the other side of the substrate to form solid state silver oxide/silver cathodes. The current collector was sprayed carbon and hydrophobic boundaries were added to isolate the device [18]. Power density and voltage output are shown in figure 17. The microbial fuel cells have the advantage of being self-reliable. Unfortunately, durability tests and lifetime values are not provided.

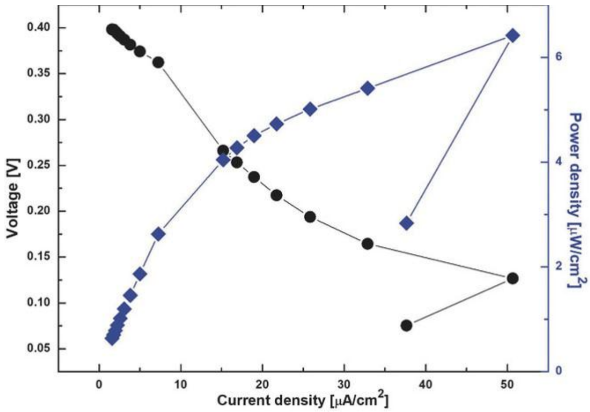


Figure 17. Power and voltage output of textile based MFC. Reprinted with permission from [18].

For energy storage, weaving super capacitive fabric into textile seems to be unattractive option. Metal organic frameworks (MOF) have large surface area, controllable pores, Nano-crystal structure and good pseudo capacitance conductive polymers. For energy storage in textile applications, conductive polymers could be used to improve electron transport by linking the isolated MOFs crystals thus providing extra pseudo capacitance. A paper by Qi *et al.* presents a one-pot metal organic framework deposited on carbon paper (MOF/CP) hybrid coated on fibrous substrate (UiO-66/Polypyrene PPY) on carbon fibers (CF). The MOFs were uniformly deposited on CF by an electro-polymerizing process in presence of dopamine additive. PPY was coated and filled into the inter-particle open space and acted as conductive links. Lastly, the fiber was coated with poly (vinyl alcohol)/LiCl gel which acts as solid-state electrolyte and separator in the fiber supercapacitor. Then the supercapacitor was obtained by twisting two-gel coated fiber electrodes together [19]. The materials used are still newly discovered and still being studied by research. This method might be too expensive and not easily repeatable. There might be specific applications in areas where it is needed, but it is not suitable for public use, due to bio incompatibility.

The next paper fabricated a high- performance supercapacitor fabricated with multi-walled carbon nanotubes (MWCNT)/molybdenum trioxide (MoO_3) nanocomposite electrodes and non-aqueous gel electrolytes. CNTs are chemically and mechanically stable, highly conductive and have large specific surface area. MoO_3 is pseudocapacitive, low cost, non-toxic, has high electrochemical activity and environmentally friendly. Composite of MWCNTs and MoO_3 hybrid nanowires is used since MoO_3 has low conductivity. The conductive fabric was made by spray coating of MWCNT/MoO_3 NW nanocomposite on stretchable fabric (82% nylon/18% spandex). The supercapacitor exhibited high capacitance and cycle stability, mechanical stability under various deformation conditions, such as folding, twisting and stretching [20]. However, the fabrication methods require special material, which increases its cost. This capacitance was made to power an attached strain sensor and it stored sufficient energy to power the sensor.

A self-maintained power system is realized by Yong *et al.* using flexible ferroelectric material for energy harvesting and a supercapacitor for energy storage. The microscopic dipole moment was created due to the change in charge distribution during polarization for ferroelectric material. When the material was deformed the charge in the electrical field was compensated by a variation in the induced charge on the electrodes resulting in net current flow. Two sheets of fluorinated ethylene propylene (FEP), which exhibited ferroelectric properties, were separated by standard polymer foam that formed a void between them. The charge was trapped on the surface of the FEP and the polymer acted as spacer and void restoring force. The energy harvesting system was combined with a carbon-based supercapacitor. An activated carbon and carbon black solution was spray coated in a controlled manner on both sides of the cotton textile. The cotton fabric acted as a separator and absorbed gel electrolyte. The energy harvesting, energy storage devices and a diode rectifier were connected together by screen printing. Both of the energy harvesting and energy storage devices were characterized separately and as a system [21]. The figure 18 and 19 describe the performance of this device. For this device, we know the energy storage unit is suitable to store what is generated, but we don't know the power requirement of the full system or the limits of application.

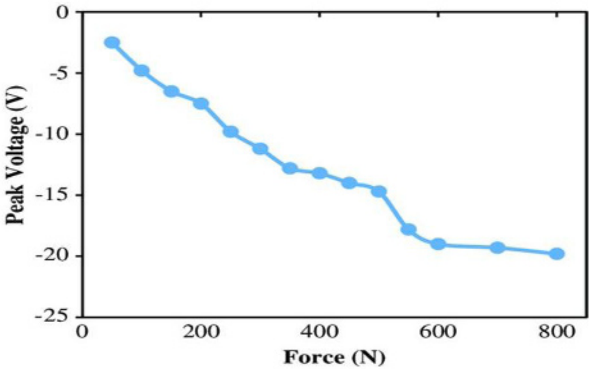


Figure 18. Peak output voltage vs. compressive force for ferroelectric. Reprinted with permission from [21].

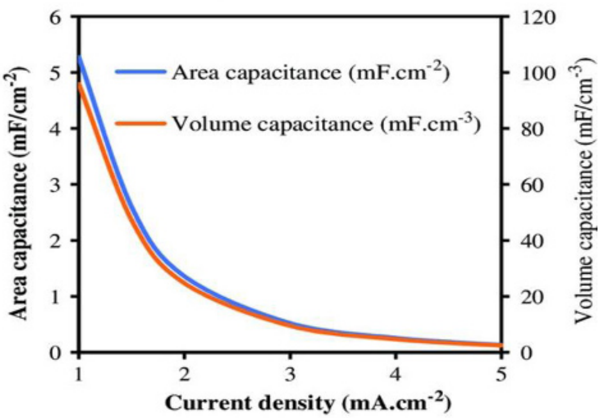


Figure 19. Current density vs. capacitance of the supercapacitor. Reprinted with permission from [21].

Activation of fabrics and active material fabrication

A material is active when its electronic property resembles that of a traditional semiconducting material. Such material can also be made conductive as most artificial materials are insulators. Currently available textiles are not active, so they need to be combined with an active material via deposition, dipping or printing. However, these methods are limited when it comes to functionality. Therefore, researchers have been looking for new methods of activation of textile material, while others focus on synthesis of new material that could be used as a substrate for textile electronics.

A simple fabrication method of ultra-stretchable metallic nanocluster films using flash deposition is realized by Venugopalan *et al*. Flash deposition of gold in a typical coil-based resistive thermal evaporator produces highly stretchable metallized elastomers at low vacuum conditions. Coil flash thermal evaporation (CFTE) is known to produce gold (Au) nanoclusters with low ionization and kinetic energies, which minimize carbonization of elastomers during deposition. CFTE deposition was made by standard deposition chamber using thermal resistance metal sources. The reported surface resistance was 25 ohm-sq-1 at 100% strain and the fabric could be stretched up to 200% based on the substrate [22]. Ma *et al.* presented a stretchable conductive adhesive material consisting of carbon nanotubes with silver particles in silicon adhesive. The MWCNT and silver microparticles are available commercially. The MWCNT were oxidized, mixed with silicone rubber, the Ag particles were added and then the compound was mixed. The resulting paste exhibited 6450 S cm-1 conductivity, which showed great stability even after 3000 stretching cycles at 50% strain [23]. Another method involving CNTs utilized the properties of natural silk, like biocompatibility and mechanical strength, to create sheathed CNT wires. Silk nanofiber films were prepared by electrospinning and then wrapped around CNT wires. The simple method keeps the conductive CNT protected and insulated. The wires have electrical conductivity of 3.1 x 104 S/m with good mechanical strength, flexibility and high durability [24]. These two methods of fabrication require specific expensive equipment and materials. However, the properties and characteristics of the films produced are excellent for textile electronics applications.

Guo *et al.* used PEDOT: PSS as an activation material for PET fabric. They used several methods for activation like inkjet printing and sponge stencil. The techniques used provided different resistance that could be tailored to fit the different applications and uses. The paper presented different characterizations, circuit fabrication and wash ability tests. They reported the sheet resistance change based on the weight of the polymer and thickness [25]. These papers present complicated and expensive methods to activate natural fabric and synthesize new fabric. They did show good properties like conductivity, stretch ability and strain resistance. Even if the fabrication method is simple or made with one step, they require professional handling and knowledge of complicated devices and expensive material.

Aside from the conductivity of the wire and interconnects, it is important to study the electrodes and their interaction with the skin. Puurtinen *et al.* presented a study on understanding the conditions that affect the efficiency of the electrodes to transfer signals and data. They used polyester yarn coated with silver paste embroidered in a circle as electrodes and fabricated five different sizes of electrodes (diameters: 7 mm, 10 mm, 15 mm, 20 mm and 30 mm). They used the electrodes to obtain bio-potential signals and studied the effect of different interface materials (dry, wet and hydrogel). They noticed that the noise level increases as the size of the electrodes decreases, which is expected for any conductive material. Also, the wet and hydrogel covered electrodes exhibited less noise than the dry electrodes. Comparisons of the measured signals with the fiber electrodes and the traditionally used electrodes [26]. The results presented in this paper prove the need for better active textile material. Hand-made electrodes are not as efficient as a fabricated one. Also, it is a generally known fact that any electrical system has more noise when reduced in size. Again, the required accuracy and sensitivity of the electrodes will be determined by the application for physiological monitoring.

Other than the activation of textiles, some efforts were dedicated to give the textile better qualities like water-proofing or self-cleaning. Choi *et al.* covered commercially available threads with Ag nanoparticles−poly(styrene-block-butadiene-block-styrene) polymer composites. This forms highly conductive and durable fibers. Then, they vapor deposited self-assembled monolayer (SAM) reagent onto the fabric. SAM allowed the fabric to be self-cleaning and waterproof without compromising the electrical conductivity [27]. The price of this method and material used is not discussed. Another paper that used commercial fabric provided a low cost and mass produced activation method. Pyrolysis strategy was used to carbonize the fabric through thermal treatment, which resulted in textile that was composed of highly conductive graphitic carbon fibers. The fibers made were used to fabricate different devices like a supercapacitor and elastic thermal therapy. This method preserved the advantages and properties of textile material like stretch ability and comfort with a scalable and easy process [28]. The method is considered low cost and less demanding than other methods. However, it still required material that is not available for large scale production.

Cataldi *et al.* presented a fabrication method for flexible and conductive cotton-based fabric nanocomposite. This was obtained by impregnation of commercially available cotton fabric with conductive ink dispersion made of graphene platelets (GPs) and thermoplastic polyurethane (TPU). The fabric shows good electrical stability even after mechanical deformation, strain application and washing. Any cracks that occur due to mechanical fatigue or strain induced incremental change in resistance but could be repaired with heat application [29]. Another method of activation that could be applied to any type of textile is the spray deposition of conductive nanoflakes, polytetrafluoroethylene (PTFE) and fluoroalkylated organosilanes. This provided a method to turn any type of fabric into conductive, breathable, antibacterial, affordable textile that could be used for energy harvesting and storage. The method cost was estimated to be less than \$0.04 per cm^2 of fabric and exhibited production of high-power density (600 μW/cm2) [30]. This was the only method which described exact cost and it is a negligible addition to normal garment price for the added functionality of textile electronics.

CHALLENGES AND FUTURE OUTLOOK

The first consideration is the application when it comes to fully functional electronic textile systems. The clothes should be suitable for the environment and usage. For example, sports-wear, firefighter uniforms or hospital garments. The only two applications of prototyped systems explored by research are for physiological monitoring and emergency operators. The water-proof ability and the endurance of these garments were not tested. Additionally, the fabrication methods were different for each device or sensor and did not consider large scale manufacturing. The charging mechanism or energy harvesting was also not discussed. These prototypes used existing devices and sensors integrated into garments. The preferred method would be to design and fabricate devices with the intention of use in textile systems thereby customizing and improving the devices for intended application.

This paper presented several examples where researchers designed and fabricated devices specifically for use in textiles. Researchers focused on one or several of the design requirements needed for textile such as flexibility, non-toxic, protection from water and environment, good adhesion to fabric, and, of course, efficiency. Sensors is the largest area of research and the sensors presented in the discussed research are reasonable while some of their efficiency is compromised as compared to solid state counterparts due to the high design requirement of all textile electronics. Researchers address these design requirements from different aspects, some focus on providing the most accurate data, others on repeatability and others on large-scale production of the fabrication methods and materials. Considering this, there is no clear method to compare devices. We need to understand the effect of the material, design and fabrication methods on the accuracy of the devices. This way we can start establishing guidelines for each type of device and application or system. For example, a garment used in professional settings might require high accuracy and signal processing; whereas a garment intended for daily and public use should be affordable.

Besides sensors, devices intended for textiles have been developed in the areas of communication, MM absorber and transistors. The research is limited in these areas because it is still not well determined how these devices would be used in a textile system or for which applications. One basic functional part that all textile systems use is a power source, either from batteries or energy harvesting. Most of the energy storage units used are super capacitors and they have been proven effective. Also, there are many energy harvesting methods, which make the textile self-charging. However, these methods are not yet efficient for a textile system containing many sensors or need a lot of energy.

Lastly, there has been research on activation of commercially available textile material. These methods are usually simple and fast from simple chemical reactions. Especially for electrodes and interconnects, activation methods are more precise than printing and stencil. Some methods of activation and synthesis are expensive and complicated but result in very efficient fabric and therefore have value for certain applications.

CONCLUSION

In this paper, we have explained the concept of textile electronics and its applications. We provided an exploration of the basic criteria and needs for this category of electronics. We then reviewed the recent advances in materials and fabrication presented by research within the past 15 years. The field is new, broad and the areas of exploration are expanding. The research shows promising progress in achieving fully functional textile garments tailored for the different uses. However, the road towards achieving affordable, reliable electronic textiles lies ahead of us.

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