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E-textile Technology Review – From Materials to Application

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ABSTRACT Wearable devices are ideal for personalized electronic applications in several domains such as healthcare, entertainment, sports and military. Although wearable technology is a growing market, current wearable devices are predominantly battery powered accessory devices, whose form factors also preclude them from utilizing the large area of the human body for spatiotemporal sensing or energy harvesting from body movements. E-textiles provide an opportunity to expand on current wearables to enable such applications via the larger surface area offered by garments, but consumer devices have been few and far between because of the inherent challenges in replicating traditional manufacturing technologies (that have enabled these wearable accessories) on textiles. Also, the powering of e-textile devices with battery energy like in wearable accessories, has proven incompatible with textile requirements for flexibility and washing. Although current e-textile research has shown advances in materials, new processing techniques, and one-off e-textile prototype devices, the pathway to industry scale commercialization is still uncertain. This paper reports the progress on the current technologies enabling the fabrication of e-textile devices and their power supplies including textile-based energy harvesters, energy storage mechanisms, and wireless power transfer solutions. It identifies factors that limit the adoption of current reported fabrication processes and devices in the industry for mass-market commercialization.

INDEX TERMS Wearables, e-textile devices, e-textile power sources, e-textile manufacturing and scalability.

I. INTRODUCTION

A wearable technology typically integrates electronic functionality into body accessories or apparels (textiles) [1], [2]. In particular, textiles are ubiquitous and are by necessity worn everywhere. This makes them the ideal application for wearable technologies. However, the current market for wearable devices predominantly consists of smart accessory devices in the form of wristbands and wristwatches [3], [4]. These accessory devices are used for fitness applications to monitor the electro-physiological activities of users [4]; and for personnel tracking and monitoring in industrial and military contexts [5]. They are typically produced using existing high throughput microelectronics manufacturing processes and materials [3], which are not ideal for electronic integration on garments or textiles in general. Although the market forecast on wearable devices is estimated to reach $US155 billion by 2027 [6], most true electronic integration on textiles are still research prototypes, and the few products on the market represent less than 1% of the global wearables market [7]. This low adoption is, in part, due to the challenges of manufacturing market-ready garments or textiles – developing manufacturing methods for wearable technologies will significantly improve their potential for industrial exploitation.

The integration of electronics with traditional textile garments produce electronic textiles (e-textiles). E-textiles are textiles that incorporate bespoke electronic functionalities for sensing (biometric or external), communications (usually wireless), power transmission, and an interconnect for sensors and other devices within a fabric [8]. E-textile

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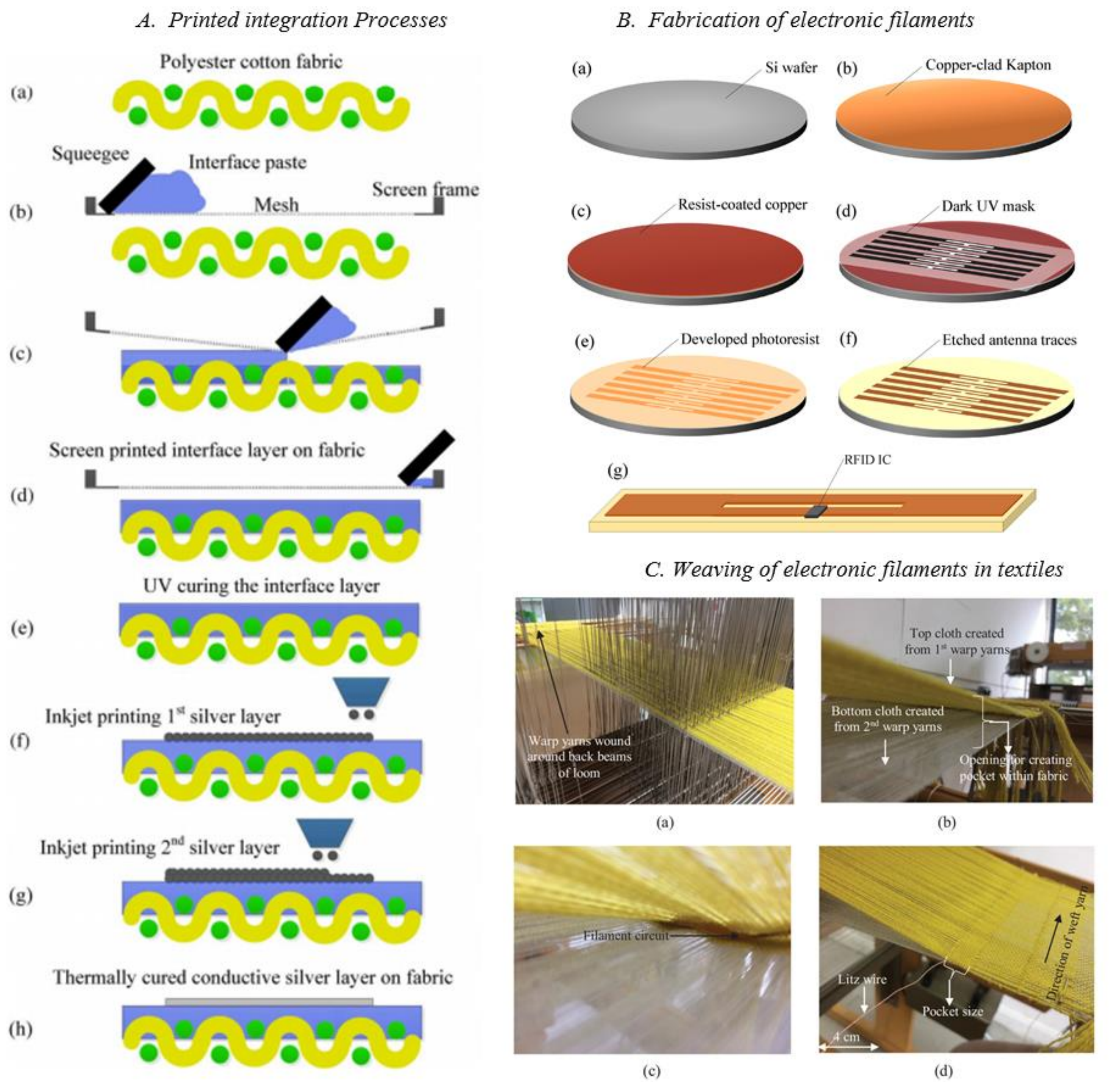

FIGURE 1: Electronic integration in textiles using printing processes [18] and the combination of electronic filament fabrication [19] and traditional textile weaving process [17]

applications include healthcare/medical monitoring and stimulation of bio-electric body signals [9] , protective garments for military and industrial personnel [10], e-textile devices for infotainment in fashion and entertainment [11], wearable energy storage devices [12] and harvesters [13] for powering mobile sensor devices, and other wearable technology. However, using conventional manufacturing processes and materials to integrate electronic functionalities onto textile substrates alters the physical properties of the textiles. To enable true integration, textile-based manufacturing processes such as screen printing, weaving, and embroidery, as well as suitable conductive materials, are required to manufacture e-textiles [14].

Retaining the textile breathability, flexibility, maintaining appearance, and "washability" after electronic integration are significant challenges to e-textile adoption. Integrated devices and materials must be robust enough to outlast the lifetime of their intended application, while delivering reliable electrical performance comparable to traditional silicon-based equivalent devices. Furthermore, novel standards and processes for safety and reliability must be defined to make emerging devices market worthy [15].

The power supplies are also very critical for e-textile devices. Many wearable accessory devices are powered from inflexible batteries which increase the weight of the devices and are required to be recharged or replaced regularly [16]. Similarly, emerging e-textile prototypes are typically powered from rigid batteries which are incompatible with the flexibility and washing requirements of textile integration. Enabling technologies for textile-based power sources, energy storage and wireless power transfer solutions that will sustainably power integrated electronics are now emerging, but these are still nascent. These significant challenges in manufacturing and powering hinder the translation of current e-textile devices from research prototypes to marketable commercial products. Therefore, this review paper scrutinizes the progress in e-textile device manufacturing and power solutions that will drive a commercialization process for these wearable e-textiles. The common fabrication processes and materials in literature and industry are initially discussed. This is followed by the state-of-the-art review on e-textiles for sensing devices, actuating, transmission of data and energy. The state-of-the-art methods for power transmission, harvesting, and storage in textiles are also discussed. The technology readiness level of the manufacturing methods is emphasized in the discussion, factoring device performance, safety and security and the scalability of the relevant manufacturing processes.

II. MATERIALS AND FABRICATION METHODS

Early e-textile devices were produced manually and comprised of off-the-shelf portable electronic devices and a power supply, connected using cables, and sewn into pockets of existing clothing [17]. In most cases, these e-textiles are only washable after the portable electronics and battery are detached. Users are required to reassemble the e-textile after washing. The earliest known example of such a device was the illuminated headband, used for electric ballet dancing, designed in 1883 by La Farandole. Other examples, such as the "VivoMetrics LifeShirt", and the "ICD+" jacket by Levi and Phillips electronics entered the market in 2001 and are now discontinued due to poor market sales. This approach to manufacturing e-textile devices was cheaper and promoted design flexibility but did not imbue the textile itself with any functionality. These early e-textiles were cumbersome to wear, and lacked the aesthetics, textural comfort, bending, and drapability that are typical of textiles. To remedy these issues, conductive materials that are compatible with mainstream textile production processes such as weaving, and printing were introduced to improve e-textile manufacturing.

The manufacturing methods for e-textiles shown in Figure 1 are considered based on the electrically conductive material (ECM) that is used for electronic integration on textiles [18], [19]. There are three ECMs commonly used in e-textiles: electrically conductive threads/yarns [14], [20], electrically conductive films [14], [21], and narrow electronic filaments [17], [22]. Electrically conductive threads/yarns are incorporated onto textiles in place of passive yarns in weaving [23], knitting [24], and sewing and embroidery [25]. They derive their conductivity from the use of flexible strands of metal yarns (e.g. stainless steel) that are wrapped within or around the core of normal textile yarns, or from metallic coatings (such as silver) of the textile yarns. These achieve conductivities in the range of 0.01 Ω/m – 500 Ω/m respectively [26]. Electronic components are often sewn on to these conductive yarns using flexible or rigid interposer circuit boards. This approach provides a reliable attachment mechanism at the cost of the textural comfort of the e-textile. Current e-textile manufacturing in industry typically combines the weaving of washable electrically conductive yarns/threads on the textile, with a lightweight and detachable portable electronic device that interfaces the user's mobile phone [27]. The woven conductive threads replace the previous use of electrical cables, offering the next level of integration. Commercial e-textile products of this type include the Adidas heart rate monitoring sports bra (2013), the Hexoskin fitness jacket (2014), Polar Bear heated garments (2017), and the Google and Levi Jacquard-enabled jacket (2017). These examples demonstrate industrial manufacturability of e-textiles but are limited to just replacement of conventional wiring. The approach in the research domain is similar; electrically conductive yarns and threads have enabled simple modular circuits and electrical interconnections in the form of transmission lines [28], electrodes [25], sensors [29], antennas [30], and transistors [31]. The durability of conductive yarns and threads is enhanced by using electrically insulating materials, such as fabric paints, and layers of non-conductive threads and fabrics [32]. These either alter the physical and textural properties of the textile or are still unreliable under stresses such as abrasion and bending [33]. Furthermore, the weave structure of the host fabric often limits the use of electrically conductive threads and the associated manufacturing methods for incorporating complex circuits on the textiles [26].

An alternative to conductive yarns is electrically conductive films and narrow electronic filaments with printing and weaving manufacturing methods. They are suitable for achieving large area (> 100 cm^2) planar circuits, or for concealing and localizing circuits within a small fabric space (< 10 cm^2) [26]. Additive manufacturing processes, such as inkjet printing [34], dispenser printing [35], and screen printing [36], have enabled electronic integration on textiles using electrically conductive inks. These inks contain conductive particles, and a polymer binder that holds the particles together [37]. These conductive inks are implemented as interconnections [21], resistors [36], piezo-resistive strain gauges [38] piezoelectric sensors [39]and electroluminescent displays [35]. Metal deposition methods, including metal plating, thermal evaporation, and sputtering have also been used to deposit metallic films on textiles [26].

Of all these methods, screen printing is most suitable for high throughput roll to roll manufacturing process and is already standard process in the textiles industry. Although these printed conductors are often not as conductive as conductive yarns (containing metallic fibers or coatings), they can achieve a sheet resistivity as low as 0.01 Ω/sq. for 25 μm thick conductive films [26]. However, screen printed conductors are typically more susceptible to damage under external stresses (e.g. from washing) which can reduce their conductivity. Other stresses such as bending, abrasion, and flexing also degrade these conductors. This lack of robustness has prevented screen-printed e-textiles from securing a significant share in the consumer application market. The Forte wireless data Glove, developed by Bebop sensors for haptic sensing (2019), exploited the use piezoresistive sensing, but uses an external circuit to calibrate the performance of the piezo-resistor. In the research domain, many applications of screen-printed e-textiles have been prototyped with durability concerns addressed by screen printing a low-cost polymer to encapsulate the printed conductor [33]. However, the encapsulation visually accentuates the electronic integration on the fabric and also affects breathability and flexibility, which is undesirable in most garments [17].

Flexible and narrow electronic filaments with widths less than 5 mm currently represent the state-of-the-art for incorporating electronic functionality on textile yarns and clothing [17], [40], [41]. This approach allows for complex circuits to be achieved on flexible plastic substrates using photolithography and etching techniques [17], or thin-film deposition techniques [40]. The functionalized filament is incorporated into the textile using standard weaving and knitting processes. Currently, there are no example products in the industry using this method to manufacture e-textile devices. Research prototypes have already demonstrated temperature sensing devices, humidity sensing, physiological sensing, and LED illumination [22], [41]. This approach is most promising technology for large scale e-textile manufacturing, but the durability must also improve. It is currently robust against more than 1500 bending cycles and over 50 wash cycles [41].

III. MATERIALS AND FABRICATION METHODS

E-textiles have been prototyped and commercialized as physiological sensors and actuators [42], activity sensors [43], environmental sensors, and visual indicator systems. These are discussed as follows:

A. PHYSIOLOGICAL SENSORS AND ACTUATORS

Wearable electrodes are fundamental elements for detection and actuation of some electrophysiological activities in the human body. They are used for measuring electrocardiogram (ECG) biorhythms that aid the diagnosis of heart conditions [9], electromyographic (EMG) monitoring for fitness and rehabilitation applications [44], electrooculographic (EOG) signals for computer control [42], and electroencephalogram (EEG) measurement for monitoring brain activity [45]. Wearable electrodes are also used in therapeutic healthcare devices such as transcutaneous electrical nerve stimulation (TENS) and functional electrical stimulation (FES). Traditional Ag/AgCl electrodes are made of hydrogel which stick directly to skin. However, these gel electrodes demonstrate reduced performance over time due to moisture evaporation and contamination build-up [46], rendering them unsuitable for long-term wearable applications. Fabric-based dry electrodes exist for wearable therapeutics and have been used in many applications including pain relief [47], stroke rehabilitation [48], [49], improving lymphatic function, and in treatment of urinary incontinence [50]. Materials suitable for making fabric electrodes include conductive yarns, silver polymer paste, and carbon polymer paste [46]-[50]. Figure 2a shows an example of a commercial knitted knee sleeve used as a TENS electrode for pain relief. The electrode can be printed on a thermoplastic film and transferred on to the textile via applied heat and pressure (Figure 2b). Alternatively, it can be printed on textile directly by printing all functional materials layer by layer [47] (Figure 2c), or a combination of the two methods above. An example of such a hybrid fabrication method is to weave the conductive yarn to form the base of the textile and the conductive path; then print the carbon electrode layer on top [48] (Figure 2d). Electrodes are integrated in a tight-fitting clothing item (e.g. sleeve, cuff, shorts) to provide good contact between the skin and the electrode. The tight fit is essential to minimize the electrode movement during exercise. These therapeutic devices (e.g. pain relief, muscle stimulation) are powered by primary batteries or rechargeable batteries. The current used in these devices are approximately 10-200 mA which is unlikely to be achieved via existing energy harvesting methods. Wireless power transfer could be adopted while considering longer charging time.

Although e-textile electrodes have been used in many applications, accurate positioning of the electrodes remains a challenge. This is of particular importance for applications where small electrodes are required to improve sensitivity of physiological signal detection, or actuation of specific muscles to achieve targeted movement (e.g. controlling individual fingers) [48]. Other considerations required in developing e-textiles for wearable therapeutics include biocompatibility (e.g. cytotoxicity, irritation, sensitization), safety (e.g. current limit), usability (e.g. easy to put on and take off), cost, and regulatory approval.

Body temperature is also a relevant physiological parameter. Wearable temperature sensors have potential medical applications for monitoring diabetic patients with foot ulcers and wound infections [51], and cardiovascular health evaluations [52]. Integrated temperature sensing functionality into fabrics is a popular research topic [51]-[53]. Temperature sensors have been printed on fabrics using

(a) (b) (c) (d)

FIGURE 2: **a) knitted electrode knee sleeve; b) electrode garment made by transfer printing; c) printed fabric electrode array [45]; d) electrode cuff made by weaving and printing [48].**

thermally responsive inks, but the poor durability of the inks limit the performance of the sensors [54]. In [55], electronic strips (e-strips) containing epoxy encapsulated temperature sensors were woven into fabrics, but this approach does not conceal the presence of the sensor from the wearer. Hughes-Riley et al. [51] improved wearability by concealing a resin encapsulated thermistor inside the core of a textile yarn for diabetic wound monitoring. The sensor achieved an accuracy within ± 0.5 °C which unfortunately is insufficient for detecting diabetic foot ulcer formation [51]. Also, the wearability of this sensor is hindered by its micro-pod encapsulation, as it is inflexible and lumpy, altering the textural feel or handle of the fabric. The state-of-the-art integration inserts encapsulated temperature sensing filaments into bespoke pockets woven within the body of the fabric [53]. The sensor is concealed from the user and does not significantly compromise the physical properties of the fabric. The thermal sensitivity of the thermistor is limited by the encapsulation material and the fabric concealment.

B. ACTIVITY SENSORS

Activity sensors are useful in fitness, training and gesture-control or movement monitoring applications. They are used for monitoring human motion and position [54], posture sensing [56], and gait sensing [57]. Example sensors include accelerometers [58], proximity sensors [59] and piezo-resistive sensors [60] These sensors are integrated with the textile as printed or coated electrically conductive or piezoresistive inks [60] woven or embroidered conductive threads [54], and commercial (MicroElectroMechanical Systems) MEMS components [61]. Current commercial applications of activity sensors from Google and Levi Strauss, and Bebop Sensors [62] are based on the integration of electrically conductive threads and piezoresistive films on the textile to achieve proximity detection and haptic sensing respectively. These electronic materials have also been utilized in the research domain to achieve similar functionalities using printing and weaving technologies with minimal compromise on the textile property. These technologies favour mass production of these e-textile prototypes as evidenced by their use in the previously mentioned commercial products. In these approaches however, external circuitry is often still required to process the sensed parameters. To limit the need for external circuitry, thin filament circuits containing MEMS-based accelerometers and proximity sensors are integrated into textiles with an in-situ microcontroller for processing sensed signals, and for giving visual feedback to the wearer about their motion through integrated LEDs [17]. Although this approach improves the wearability of the textile in that the integrated electronics are completely concealed from the wearer, the manufacturing e-textiles using this technology would require a mechanism for automating the insertion of these electronic filaments into the textile during weaving.

C. ENVIRONMENTAL SENSORS

E-textiles can be useful as environmental sensors for detecting or monitoring gas pollution and humidity changes. E-textile sensors for detecting toxic gases in the environment can be bound directly on the textile [63], or with the use of flexible polymeric substrates, which can be woven into the textile [53], [55]. Sensing of concentrations of ammonia trimethylamine, ethanol, and carbon dioxide gases have been implemented using chemo-resistive sensing techniques. In these techniques, a change in concentration of a target analyte gas results in a corresponding change in the resistance of the sensing material. A similar capacitive sensing technique can be used to detect dielectric changes [63]. The techniques are implemented using the deposition of particular materials either directly onto the textile or on polymer substrates, including graphene oxide, MWCNTs, PVC, Cumene-PSMA, PSE and PVP, ZnO nano particles and silver nanowires [63]. For example, Yun et al. [64] demonstrated a washable ammonia gas sensor on lab coat using a graphene oxide coated cotton yarn. The sensor, which was fabricated by electrostatic assembly of the graphene oxide on a cotton yarn, exhibited good chemical durability and high sensitivity to NO_2 analyte gas. Similarly, silver interdigitated electrodes have been embroidered with a drop casted polymer/MWCNT on a cotton textile enabling the detection of ethanol, ammonia, and trimethylamine. Finally, spray coated, spin coated, and inkjet-printed gas sensing materials have also been implemented on thin (50 µm) flexible filaments that contain thermally evaporated electrodes which detect acetone vapor [55], [64]. The filaments were consequently woven into a textile with minimal compromise of the properties of the textile. These filaments survive the weaving processes and are capable of withstanding bending radii as low as 165µm if the resistance change in the sensor measurement is differentially compensated.

Humidity sensors are incorporated into textiles using flexible substrates (Kapton, polyethylene terephthalate (PET), and parylene) containing a collection of thin conductive film humidity sensors stitched or woven into the textile [64], [65]. These sensors may also be deployed directly on the textile by the printing [66], [67] or embroidery of conductive yarns [68]. Example sensing materials include stainless steel yarns [68], PEDOT:PSS [65], cellulose acetate butyrate (CAB) [68], and polymer electrolytes like polymethyl-methacrylate (PMMA) and Nafion® (sulfonated tetrafluoroethylene based fluor-polymer-copolymer) [66] Depending on the sensing material, humidity is measured from the change in electrical conductivity of the material or determined by monitoring the change in the dielectric constant of the sensing material. The integration of humidity sensing functionality into fabrics by printing is easy to manufacture at scale, however emerging prototype devices have poor long-term stability, limited wash resistance and can have a slow response time.

V. ENABLING TECHNOLOGIES

A. DATA AND POWER TRANSMISSION

Reliable wireless connectivity is essential for wearable applications [69]. Electrically conductive wires are commonly used to facilitate data and power transfer; such wires must be flexible and must be sewn or glued into the seams of the garment. Currently, the bus standards, textile cables, or washable interconnects are not clearly defined. A mix of wires, textile yarns, and elastic weaving methods with custom, specific connectors are combined in order to achieve flexible transmission, though due consideration is given to the challenge of controlling the strain of the wires to prevent breaking over repeated garment use. For some applications, cables should be shielded to isolate radiation and radio interference. Due to this challenge wireless methods are preferred. On-body conformable antennas, wearable antennas, and fully-textile antennas are essential for a reliable wireless link, and to enable applications such as Radio Frequency (RF) Energy Harvesting (EH) and RF Wireless Power Transfer (WPT) [70]. Textile and wearable antennas have been studied extensively; in [71], fabrication techniques, applications and state-of-the-art performance metrics are surveyed. Applications such as RFID [72], RF-EH [73], and on- and off-body high data-rate communications have been proposed [74]. The trade-off between realizing the Body Area Network (BAN) antennas using textiles or other wearable surfaces such as accessories and buttons have been explored in [75], demonstrating the benefits of non-textile antennas in terms of performance and separation from the body. In this section, antennas and propagation in the e-textiles eco-system are surveyed from a performance and application point of view, reviewing the design trade-offs between optimal antenna characteristics, and the user's experience.

1) RF TEXTILE MATERIALS: COMFORT AND PERFORMANCE

Many fabrication methods have been proposed for textile antennas [71]. Achieving high antenna figures of merit: S11 bandwidth, radiation efficiency and radiation patterns, while maintaining the user's comfort and utilizing simple low-cost fabrication processes is the objective of textile and wearable antenna design. Embroidered [76], [77], [78] and adhesive backed conductor panels on conductive fabrics [73], [79] benefit from utilizing fully-textile radiative elements, which approach the conductivity of solid copper enabling high radiation efficiencies. At mmWave frequency bands, realizing small feature size and homogenous conductors is essential to achieve high radiation efficiency, where the homogeneity of the conductor is paramount to minimizing insertion losses [80]. Laser-ablated copper tape [74], [81] and etched copper- laminates [82] have been used to realize mmWave textile-based antennas and complete flexible body-area network nodes [83], with similar performance to their counterparts on rigid substrates. Solid copper (using photolithography or laser ablation) offers improved conductivity and conductor pattern resolution over electroplated conductive fabrics [74]. However, large area solid conductors may compromise the fabric's breathability, which motivates using conductive fabrics wherever the minimum feature size can be resolved.

Hybrid fabrication approaches have been proposed to improve integration of RF components in e-textiles. Integration of a thin, flexible antenna filament in a textile weave to produce an RF-yarn has been proposed in [84]. Novel approaches, such as metamaterial textiles, have been realized using conductive fabrics for improved power confinement around the body for on-body communication [85]. While the impact of textile antennas on the fabric composition has not been investigated in detail, the

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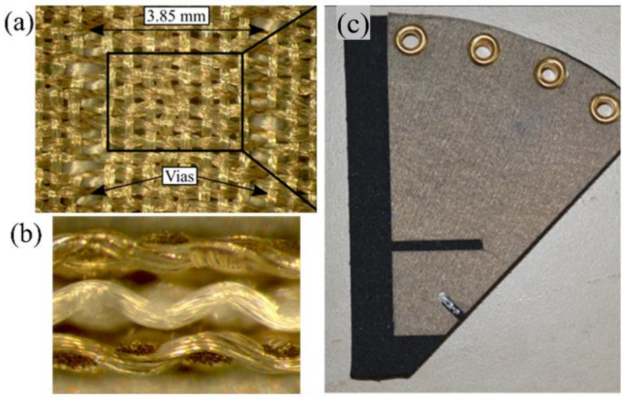

FIGURE 3. Textile-based SIW structures: (a) mmWave SIW transmission line using conductive threads [89], (b) close-up view of the conductive thread vias [89], (c) sub-1 GHz RFID SIW antenna [88].

conductors utilized are lightweight and do not significantly impact wearability. Furthermore, non-textile wearable antennas reported in [75] are integrated in existing clothing features, such as buttons and logos, making them an attractive alternative to fully-textile antennas. Wearable antenna design, both on textiles and other flexible substrates, have focused on isolation using ground planes (e.g. patch antennas) at microwave bands [73], [79], or through re-tuning antennas when shielding is not possible for applications such as insole antennas [83]. At Very High Frequency (VHF) or lower Ultra-High Frequency (UHF) bands, where isolation is not feasible due to the longer wavelength, the main aim is to ensure the antenna maintains its S11 bandwidth in proximity of the body [86]. At mmWave bands, standard antenna designs such as patch arrays [74] and end-fire Yagi-uda [81] shows that textile antennas can be optimized for certain radiation patterns based on the application. Novel geometries have been proposed to improve the bandwidth and efficiency, along with the potential of using the human body as a reflector at mmWave bands given a minimum clearance of 4 mm [80].

2) MANUFACTURING AND SCALING TEXTILE ANTENNAS

A key design issue for the fabrication of textile antennas is the considerable variation in dielectric properties between fabrics. The relative permittivity and dissipation factor of multiple textiles have been measured in [79]. To expedite mass production of patch antennas on textiles, [87] proposed a method of comparing the simulated and measured maximum return loss around 2.4 GHz to extract the substrate's dielectric properties. However, patch antenna development has been mostly limited to felt or pile fabric substrates [73], [79], [18] due to their lower dissipation factor (tanδ) and higher thickness than most woven fabrics enabling higher radiation efficiencies.

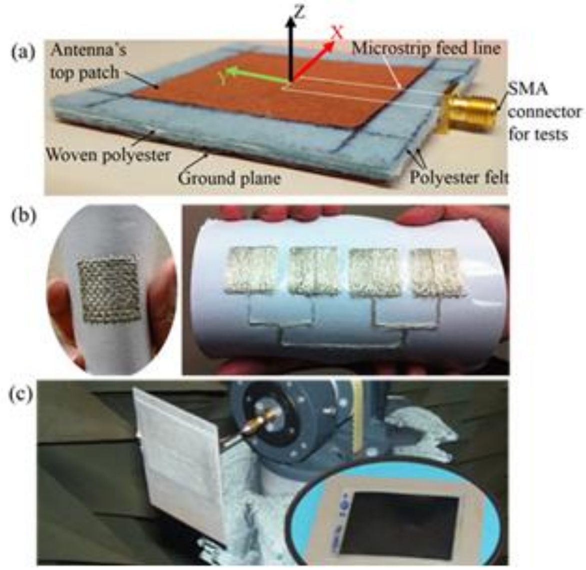

FIGURE 4. Textile-based patch antennas realized using: (a) adhesive backed conductive panel on conductive fabrics [79], (b) embroidery of conductive thread [95], (c) inkjet printing on interface layer [18].

Multiple processes and materials have been proposed for fully-textile antennas based on conductive threads. Novel embroidery processes allow resolutions down to 0.1 mm feature sizes [78]. The impact of stitching patterns has been studied in [88] showing up to 12 dB variation in gain for varying weaving direction. Substrate-Integrated Waveguides (SIW), a common structure for microwave and mmWave antennas and transmission lines, have been presented using conductive threads [89] as an improvement over punctured vias [90]. The improved isolation of SIW antennas has been demonstrated with flexible solar cells integrated on the antenna's ground planes for improving area utilization [91]. Figure 3 shows textile SIW for mmWave applications using conductive threads rigid vias for sub-GHz RFID [92].

Additive manufacturing has been proposed by printing antennas either directly on textiles using interface layers [18], or onto a polyimide substrate (for prototyping) [93]. However, printed interface layers have significantly higher dissipation factor, (tanδ>0.04) compared to fabrics as measured in [79], resulting in dielectric losses, which reduces the efficiency of the antenna. Thus, the textile antennas based on woven or adhered conductive fabrics have been able to achieve radiation efficiencies over 70%, whereas their printed counterparts achieve a maximum of 50% efficiency on an interface-textile combination. Screen-printing has been used to realize textile antennas up to 77 GHz for imaging applications [94]. Figure 4 shows textile patch antennas realized using different fabrication techniques using adhesive backed conductive panel on conductive fabrics [79], embroidery of conductive thread [95], inkjet printing on interface layer [18].

2) SAFETY CONSIDERATIONS AND APPLICATION-SPECIFIC TRADE-OFFS

The Specific Absorption Rate (SAR) of a textile antenna defines the safety of operating it near the body [96]. 3D Electromagnetic (EM) simulation is widely used to evaluate the SAR of textile antennas modelled in proximity of human phantoms or tissue models [83], [97], [98]. Certain textile antenna applications impose additional requirements on the radiation of the antenna. For instance, textile antennas for medical imaging need to radiate into the body [99], unlike antennas radiating off-body for communicating with a non-wearable device, or on-body communicating with other antennas worn by the same user. Although shielding in this case becomes less relevant, compliance with SAR regulations is crucial. The design of an e-textile antenna is a multi-parameter optimization problem. The efficiency of the antenna, and subsequently its gain, are a direct function of the conductivity of the materials and type of fabric (substrate's thickness and tanδ). Performance in proximity of the body is a design driver that may constrain the choice of antenna to isolated antennas using reflectors, or solid ground planes, though this choice increases the thickness of the antenna, especially at lower frequencies.

B. POWER MANAGEMENT AND ENERGY HARVESTING

Incorporating "intelligence" into an e-textile system is a significant challenge [100] and is typically limited by available power. In systems powered by rechargeable batteries, it is desirable to minimize battery size and still deliver a maximum lifetime between charges whilst maintaining user acceptable weight and dimensions. Reduction in the power consumption of the system drives a reduced battery size, for consumer and manufacturer benefit.

For systems that are powered by energy harvesting, they are dependent on the dynamics of the incoming power as well as the demands of the system. Energy-neutral systems aim to harvest as much energy as they need over a period of time, and the system may respond to changes in its energy supply by adjusting its duty-cycle [101]. Unfortunately, the dynamics of an energy harvesting system are not typically matched to the dynamics of demand: while a system may wake up periodically to take measurements, process data, transmit wirelessly, and then re-enter sleep mode, an energy harvester may give a relatively low level of current that is unable to directly supply those peaks of activity [102]. Additionally, energy may not be harvested at the time when it is needed: overnight, for example, from a photovoltaic cell. This may mean that, even with energy harvesting, a relatively large energy storage device may still be required to remedy the short-term mismatch between supply and demand.

To reduce the power consumption of systems, minimum-energy approaches involve running microcontrollers at significantly reduced voltage [103] (near- or sub-threshold), bringing substantial benefits for power consumption. A limited number of subthreshold devices are now available commercially. Energy harvesting circuits may be integrated with these ultralow power microcontrollers, reducing the component count and hence the spatial dimensions of the system [104], although this integration has not seen significant commercial use. Another recent innovation is in transient computing: removing the need for energy storage by allowing systems to use power when it is available, and by making use of non-volatile memory to permit computation to span several power cycles [105], at a potential spatial cost. Whilst this means that energy storage can be kept to a minimum, it is only suitable for applications where computation is needed when energy is being harvested, constraining this technology to a smaller market share.

TABLE I.
SUMMARY OF ENERGY HARVESTING TECHNOLOGIES FOR E-TEXTILE DEVICES AND LARGE DEVICES

Energy harvesters	Power output of E-Textile devices	Power output of non-wearable devices
Ferroelectricity	5.6 μW/cm^2 [106]	214 μW/cm^2 [107]
Piezoelectricity	1.1-5.1 μW /cm^2 [108], 1.9 μW/cm^3 [109]	64.9 μW /cm^2 [110]
Triboelectric	1.88 mW/cm^2 [111], [112]	120 mW/cm^2 [113]
Thermoelectric	44.4 μW/cm^2*[114]	600 μW/cm^2 [114]
Electromagnetic	8.7–2100 μW/cm^3 [115]	100-300 μW/cm^3 [116]
Electrostatic	0.5–100 μC/cm^{2}K [117]	9 μW/ cm^2 [118]
Radio Frequency	PCE=50.5%, at 0.25 μW/cm^2, at 820 MHz [119]	PCE=50% at 0.22 μW/cm^2, at 2.4 GHz [120]
Photovoltaics	PCE=10%, 10 μW /cm^2 [121]	PCE=47.1%, 47.1μW /cm^2 [122]

*Location on wrist

For most wearable applications, conventional batteries are not ideal because they require periodic replacement or charging, and typically have a bulky form factor. Consequently, for wearable applications, a demand exists for energy supply systems that accumulate energy dissipated by the human body. Typically, in an e-textile context, energy is generated either internally from human body movements or temperatures, or externally from environmental factors. Energy generation mechanisms dependent on user motion include ferroelectricity, piezoelectricity, and triboelectricity. Mechanisms for external generation of energy include wireless power transfer, and photovoltaics while thermoelectricity generation depends on the gradient between internal (from the human body) and external/ambient temperatures. The maximum power output reported of each energy harvester for wearable and non-wearable devices is mentioned in Table 1. There is still a large discrepancy between the wearable and non-wearable energy harvesters, except for the RFEH rectennas which achieves the same performance for textile and non-textile implementations [119]. The discrepancy in other harvesters is due to limitations in size, material, and environmental factors. The

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following sections discuss the limitations in designing wearable energy harvesters, current research, and directions for commercialization.

1) FERROELECTRICITY

Piezoelectricity is an electrical charge generated inside certain materials when they are subjected to external mechanical stress. Porous polymers which present strong piezoelectric-like properties under a high electric field, are classified as ferroelectret materials [123]. Due to their outstanding piezoelectric properties, ferroelectrets have attracted interest in wearable energy harvesting applications. Ferroelectrets are typically arranged as irregular cellular macro-sized voids in which the breakdown of air within the voids during a corona polarization results in a permanent internal dipole moment. Ferroelectrets exhibit a strong piezoelectric effect due to the combination of the internal dipole moment and the porous cellular structure. Ferroelectrets also display hysteretic, permanent, reversible, and spontaneous electrical polarization from an external electric field. When the ferroelectret is subject to a strain or a temperature change, to maintain the electrical neutrality of the whole material, the electrical field in the void is compensated by the induced charge on the outer surface of ferroelectret (generated by the change in internal dipole moment). Compared with Polyvinylidene fluoride (PVDF) and Lead zirconate titanate (PZT) with pyroelectric coefficients of 27 μC/cm^{2}K and 450 μC/cm^{2}K, respectively, ferroelectrets exhibit much smaller pyroelectric coefficients of 0.25 μC/cm^{2}K [124]–[126]. This means their performance is less sensitive to temperature change, which is important for a body-worn harvester.

Energy-harvesting systems with ferroelectrets include cantilever-based systems and nanogenerator based devices, as well as devices incorporating ferroelectrets with other nanogenerators [127-130]. The power generated by these devices ranges between 2.5 nW to 0.5 mW, which is sufficient to power a sensor, but not enough to power a complete wearable electronic system. In addition, the operating frequency for these reported harvesters ranges from 5 Hz to 30 Hz, which is higher than the frequency of body motion (3-17 Hz). Therefore, these energy harvesting systems using ferroelectret may need to be redesigned to be optimal for wearable applications.

Ferroelectret energy harvesters in e-textiles are either integrated or non-integrated depending on the deposition method used. Shi et al. [131] designed a ferroelectret by sandwiching a layer of standard polymer foam between two fluorinated ethylene propylene (FEP) sheets. This approach provides a standard, simple fabrication process that can be used with any standard textiles. The study also defines a theoretical model for predicting performance of textile ferroelectrets. Based on this concept, Yong et al. designed a textile power module combined with a textile ferroelectret harvester, and textile supercapacitor, on a single textile [132].

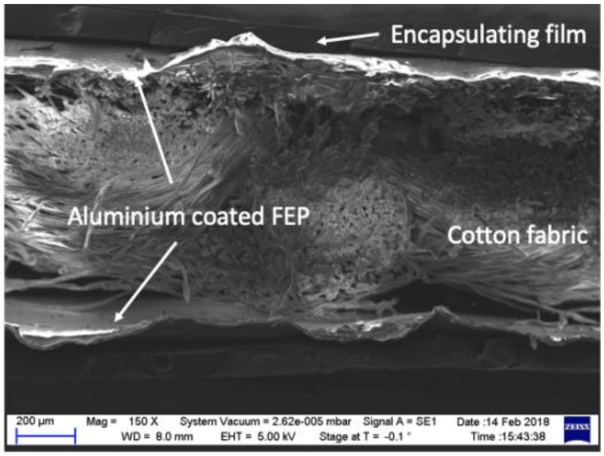

FIGURE 5. Cross-sectional scanning electron micrograph of a textile ferroelectret structurer with the cotton layer sandwiched between the FEP films with aluminum electrodes and protective encapsulation [132].

The textile ferroelectret is fabricated from two FEP sheets separated by a standard cotton textile, as shown in Figure 5. For the textile ferroelectret harvester, the textile acts as a flexible support material to replace the cavities inside the ferroelectret. The integrated textile ferroelectret can generate electric energy with an instantaneous output of around 10 V and power density of 0.86 μW cm^{-2} across a 70 MΩ resistance load under a compressive force of 350 N. However, this textile ferroelectret shows deterioration in the output after 21000 compressive cycles. The advantage of this method is that it reduces the complexity of device packaging. Although the energy output of the harvester is lower than that of the non-integrated harvester, the overall energy output can be enhanced by increasing the area and distributing the storage across a garment, a key advantage of this technology.

2) PIEZOELECTRICITY

Piezoelectric materials convert mechanical energy to electrical energy and vice versa. These materials have been used for the development of wearable textile harvesters that exhibit high sensitivity, stable energy conversion and good mechanical properties [133]. Piezoelectric materials used in e-textiles are categorized in three main groups: piezoelectric ceramics, polymers, and composite materials. A conventional piezoelectric ceramic has a polar tetragonal or rhombohedral perovskite structure below the Curie phase transition temperature. Piezoelectric ceramics can be found in bulk, porous and nanofiber forms [134]–[136]. Lead Zirconate Titanate and its associated materials present the best piezoelectric performance, and from their discovery in the 1950s they have been extensively used in the fabrication of sensors [137]. Since PZT contains lead, which is toxic and harmful to the environment, the use of this material in wearable applications is restricted. This problem can be addressed by substituting lead-free perovskite oxides like Barium Titanate, Bismuth Strontium Titanate, Calcium

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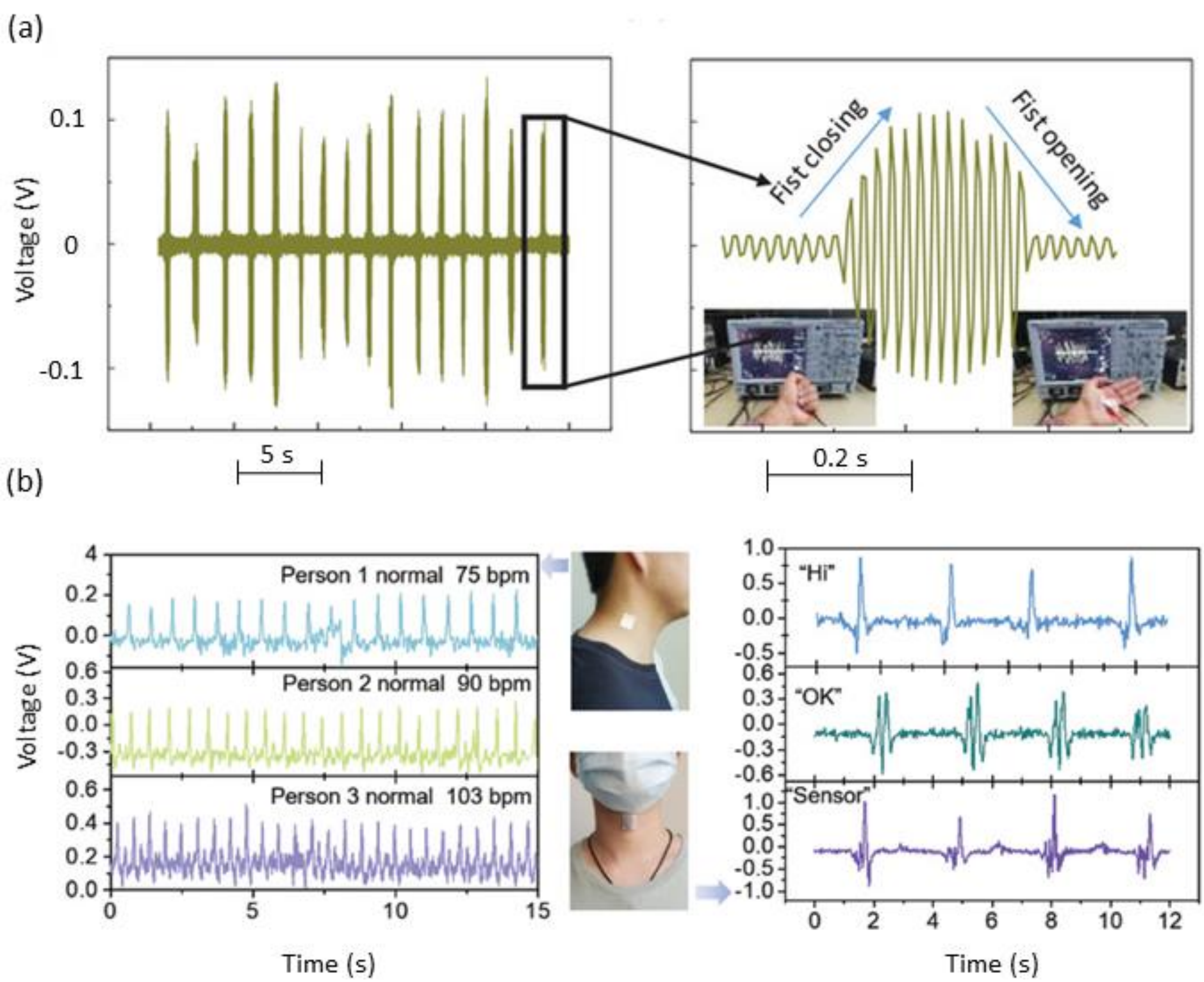

FIGURE 6. **(a) Real-time body motion monitoring by a piezoelectric fiber sensor attached on a palm: The output signals generated upon opening and closing of the fist, and photographs of the piezoelectric fiber sensor attached to the hand [Copyright 2021, John Wiley and Sons] [168], (b) Pulse waveforms of different users when wearing the fabricated MFP textile on the same position of their necks, and the dynamic output profile for spontaneous voice recognition when saying different words, [Copyright 2021, John Wiley and Sons] [169].**

Titanate, Potassium Sodium Niobate and Potassium Niobate [138]. PZT, $BaTiO_3$ and ZnO are the most common piezoceramics for piezoelectric fiber fabrication [139]–[141]. However, when compared to piezoelectric polymers, bulk ceramic oxides are more brittle, and have a lower piezoelectric voltage constant [142], which limits the use of these materials for the large-scale fabrication of wearable textiles. Piezoelectric polymers have been recommended as a solution to these issues, as they are more flexible, cheaper, and easier to process. This category of polymers includes polyvinylidene fluoride (PVDF) and its copolymers, several copolymers of vinylidene cyanide (VCDN), some nylons as well as aliphatic and aromatic polyurea. PVDF is a semi-crystalline thermoplastic polymer material with good chemical and thermal resistance [143]–[144] which is well known for its stable and high piezoelectric properties from its β crystalline structure [145–146]. The PVDF family also includes copolymers of PVDF with trifluoroethylene (TrFE) and tetrafluoroethylene (TFE) with higher crystallinity, thus enhanced piezoelectric performance [147]–[148]. Piezoelectricity has been observed in Nylon 11 electrically polarized at the temperature range of 70-90 °C [149] as well as Polyurethane elastomer (PU) [150]. Lastly, P(VDCN-VAc) copolymers also exhibit high piezoelectric properties comparable to those of PVDF when polled at 150 °C under an electrical field in 20-60 MV/m. Among the polymer piezoelectric materials, PVDF and P(VDF-TrFE) display the best piezoelectric response ($d33 \approx -30$ pC/N) [151] and are widely used for piezoelectric e-textile fabrication as they exhibit opportune properties in terms of easy processing, chemical resistance, structural flexibility, biocompatibility, and good mechanical strength [152]. Recent research suggests the use of metal nanoparticle, carbon nanotubes, graphene, zinc oxide or barium titanate [153] in order to enhance the formation of β piezoelectric phase in PVDF. Piezoceramics are usually attached on fabric substrates, whereas piezopolymers are directly used for the fabrication of nanofiber webs or nets. Composite materials combine the properties of both ceramic and polymer materials to provide enhanced actuating and sensing performance. The mechanical and the dielectric behavior of polymer composites can be improved by choosing an appropriate piezoceramic as the reinforcing phase. The use of piezoelectric composite materials in the e-textile industry can be significantly more beneficial than using conventional piezoelectric generators. Piezocomposites exhibit higher flexibility and lower leakage current; they offer a mass production and low-cost option to harvest mechanical forces with increased electrical output [154].

Different fabrication methods based on coating [155]–[156], spinning [157]–[158], plating [159], printing [160]–[161] and injecting [162], have been used to produce electrical textiles. The most common are the melt-spinning and the electrospinning processes. The former has the advantage of low-porosity fiber production and high fiber diameter control [163]. However, in the latter, no further polling process is necessary due to the application of the high electric field during fabrication. However, electrospinning is more expensive and challenging, thus less applicable to mass production [164]. To collect the piezoelectric generated charge, electrodes can be coated or wrapped in core-shell structures in a sandwiched metal-insulator-metal arrangement [165]. Based on the structural characteristics, piezoelectric e-textiles can be grouped in three main categories: single fiber-based structures, textile formed fabric-based structures and multilayer stacked fabric-based structures [166].

The following examples highlight some of the recent key achievements in the field of piezoelectric e-textiles for energy harvesting applications. Anwar et al. [167] used the electrospinning method for the fabrication of nylon-11 nanofibers from nylon-11 in TFA:acetone solution. In this research, the interplay between the solvent mixture, the evaporation rate, the pulling force acting on the fiber, and the fibers' diameter all play a decisive role in the formation of the self-poled, highly piezoelectric δ′-crystalline phase. The fabricated nanofibers produce an output voltage of 6V under mechanical impact, as shown in Figure 6a. Finite element models show that the output voltage increases when porosity is induced into the fibers. Su et al. [168] demonstrated an alternative approach, where they developed a muscle fiber inspired (MFP) nonwoven composite piezoelectric textile for wearable healthcare monitoring applications. To mimic the muscle fibers, polydopamine (PDA) was dispersed into the electrospun barium titanate/polyvinylidene fluoride (BTO/PVDF) nanofibers to enhance the interfacial adhesion, mechanical strength, and piezoelectric properties. More specifically, a 3.02 wt% PDA doping into the BTO/PVDF composites increased piezoelectric voltage by 47%. Their improvements were both confirmed by experimental data and phase-field simulations. The fabricated nanofibers exhibit a sensitivity of 3.95 V/N and stability decline of <3% after 7,400 cycles. Figure 6b presents further information on the performance of the fabricated MFP textile.

Despite the great progress of piezoelectric e-textiles in theoretical research, there is a considerable gap between research and practical commercial applications. The literature shows that most of the piezoelectric e-textiles to date are manually fabricated. There are also difficulties related to low production capacity, long, slow and expensive manufacturing techniques, inadequate integration methods, and power output inefficiency that must be overcome before any commercial products using these technologies can be developed.

2) TRIBOELECTRICITY

Another energy harvesting technology is that of the triboelectric nanogenerators (TENG) which operate on the principle of triboelectrification and electrostatic induction. Such technology has been proven as energy harvesters for self-powered wearable applications [169]–[171]. The triboelectric effect is generated by regular contact between a material that gains electrons and a material that loses electrons, where the output performance changes in proportion to the mechanical energy applied to the TENG. Their advantages include broadband behaviour, high energy density, lightweight, ease of fabrication using low-cost, readily available materials, and different operating modes (contact separation, sliding, single-electrode and free-standing modes) [172]–[173]. Additionally, as the output performance of a TENG relies on the active materials and device structure, the maximum generated power density has been reported to be up to 1200 W/m2 working in a slide-mode, for an advanced triboelectric system based on thin layers of polymer-metal triboelectric contact [111]–[112]. Consequently, applications and challenges to enhance the output performance in wearable TENG focus on harvesting energy from human motion using electronic skin (E-skin)/human skin, fibers, yarns, and fabrics/textiles [174].

Firstly, due to the large surface area of the skin on the human body, an e-skin (an artificial skin made of flexible materials and electronic components) is designed as a triboelectric layer to generate charge using contact electrification [175]–[178]. The e-skin gets positively charged when in contact with most common polymers (which in turn become negatively charged) [179]. Furthermore, these devices (Figure 7a) [176], [180]–[182] can generate a maximum output voltage, current density, and power density from ~70 V to ~180 V, ~2.7 μA/cm^2 to ~2.8 mA/cm^2, and ~500 mW/m^2, respectively [176]–[178], [180]. This is sufficient, for example, to operate as a motion sensor that measures the angle (rate) of human finger joints. Furthermore, it can be used for monitoring the localized touching actions of human skin with a detection sensitivity of pressure 0.29±0.02 V/kPa [176]. Consequently, the E-skin/human skin-based TENG can harvest biomechanical energy that can be used to power body worn sensors [176], [180]–[182].

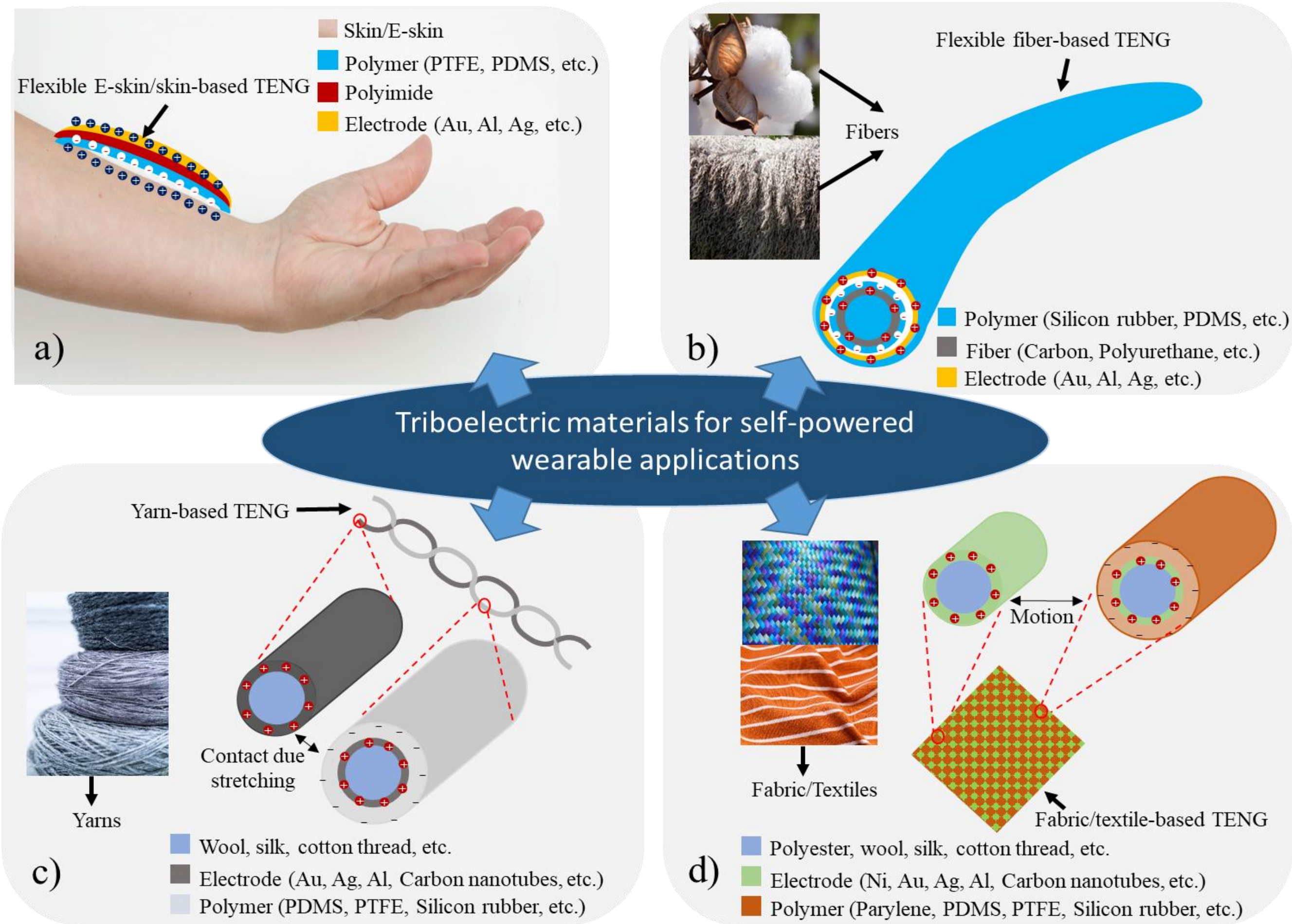

FIGURE 7. TENG for self-powered wearable applications: a) Skin-based TENG with triboelectric contact between polymer-skin. b) Fiber-based TENG with triboelectric contact between conductor-polymer/fibre. c) Yarn-based TENG with core-sheet yarn with triboelectric contact between yarn/conductor-polymer/conductor/yarn. d) Fabric/textile-based TENG with triboelectric contact between textile/conductor-polymer/conductor/textile.

Secondly, the use of textiles, fibers and yarns as triboelectric materials has demonstrated significant progress in the fabrication of wearable TENG devices. These are categorized as 1-D-structure for a fiber TENG (Figure 7b) [181], [183]–[186] and yarn TENG (Figure 7c) [171], [187], [188]–[189]. Fiber TENGs work based on the interaction within the core-shell of the textile fiber. Fiber TENGs are able to harvest multidirectional mechanical energy and have been used as self-powered acceleration or strain sensors based on the deformation of the fiber materials and the use of wire conductors materials as electrodes [183],[187],[189]. However, fiber based TENGs give low triboelectric output due to the limited operating area in the fiber core. The yarn TENG contains multiple textile fibres and can work in contact-separation mode delivering higher output power and mechanical strength. TENG devices with 2-D structure that are implemented on fabrics/textiles surfaces (Figure 7d) [190]–[195] provide more configurations of operation, triboelectric materials for the fabrication as in situ functional finishing and post weaving processes [196]–[199]. The fiber TENG can also be woven into 2-D textile TENG devices. Textile-based TENG are easy to integrate with other functional devices, including batteries, supercapacitors, and solar cells. This combination produces a hybrid self-charging power textile for wearable systems [200]–[203]. Overall, the aforementioned devices are able to generate a maximum output voltage, current density, and power density from ~24 mV to ~1050 V, ~10.5 nA/cm^2 to ~11.25 µA/cm^2, and ~0.38 nW/cm^2 to ~1.88 mW/cm^2, respectively [171], [181], [183]–[186], [188], [195]–[202], [204]–[205].

Key challenges and improvements on e-skins and other TENG devices remain. To achieve the output power density values produced by advanced triboelectric systems [111–112], research must be driven by the performance figure of merits (FOM) [206]. Designs with a suitable structure, that preserve the intrinsic merits of the material's size and flexibility, are required. For textile-based TENG devices, this would necessitate the optimization and improved surface engineering current triboelectric materials on textiles using novel techniques that guarantee better electrical outputs. These methods must also benefit scalable manufacturing without compromising the wearability of the textile.

2) PHOTOVOLTAICS

The textile substrate places many constraints on the fabrication of the devices, which means existing processes and technologies cannot be simply applied directly onto the textile. Textiles are highly flexible substrates with different mechanical structures depending upon, for example, the weave and yarn parameters. The textile surface is porous and very rough compared to a plastic substrate, such as polyimide film (Kapton, trade name of Dupont) and their use will limit the maximum temperature that can be used in device processing.

Commercially available textile solar cells use conventional rigid silicon or plastic solar cells, as standalone Photovoltaic (PV) devices, which are attached (stitched or glued) onto the fabric as a functional patch [207]. This approach makes the textile relatively inflexible, non-breathable and alters the texture of the textile dramatically. In addition, the textile itself has no inherent functionality, but significantly increases in weight since it only serves to house the off shelf solar cell products. A new generation of flexible dye-sensitized solar cells (DSSCs) and organic solar cells (OSCs) offer a solution that integrates into the textile itself. It provides a low weight solution that maintains the feel of the fabric. However, reliable integration of DSSCs and OSCs on fabrics must balance the requirements for device performance, flexibility, and durability. The energy conversion efficiency of current prototypes of DSSCs and OSCs on fabrics must improve. The fabrication processes are currently not compatible with the textile industry. Encapsulation techniques to provide durability against washing are still required.

Fabric OSCs were mainly fabricated using a combination of evaporation and spin-coating, as exemplified by Bedeloglu et al. [208]–[211]. That work used a non-woven polypropylene textile tape as the substrate, which is not representative of typical woven fabrics with achieved 0.2% efficiency. Krebs et al. [212] used a standard woven textile and smoothed the surface by laminating a polyethylene film for OSCs. This film has a low surface energy and requires a plasma treatment to enable subsequent films to be deposited. These films were deposited by a combination of screen printing and evaporation. However, it did not function due to short circuiting. Another approach by Lee et al. [213] fabricated OSCs on a flexible Polyethylene Terephthalate (PET)/Indium Tin Oxide (ITO) substrate, which was then attached to a conductive fabric which acted as the bottom electrode. This approach does not add functionality to the textile itself and uses evaporation processes for some of the films. Other research has explored fabricating a functional organic PV fiber, which can then be woven into a textile [214]–[217]. This approach demonstrated a maximum efficiency of 0.5%, but the method fundamentally limits the output of the solar cell, because once woven into a textile, the PV layer is inevitably partially shaded. Krebs' group reported serially connected tape weaved OSCs on textiles via roll to roll processing with active area of 368 cm^2 and achieved efficiency of 1% [218]. Inorganic solar cells on fabrics have also been demonstrated as evaporated Copper indium gallium selenide (CIGS) PV textiles with a reported efficiency of 13% [219]. This is a promising value; however, the evaporation-based fabrication method is not compatible with large scale textile manufacture, and the toxicity of the inorganic material remains a significant concern for wearable applications.

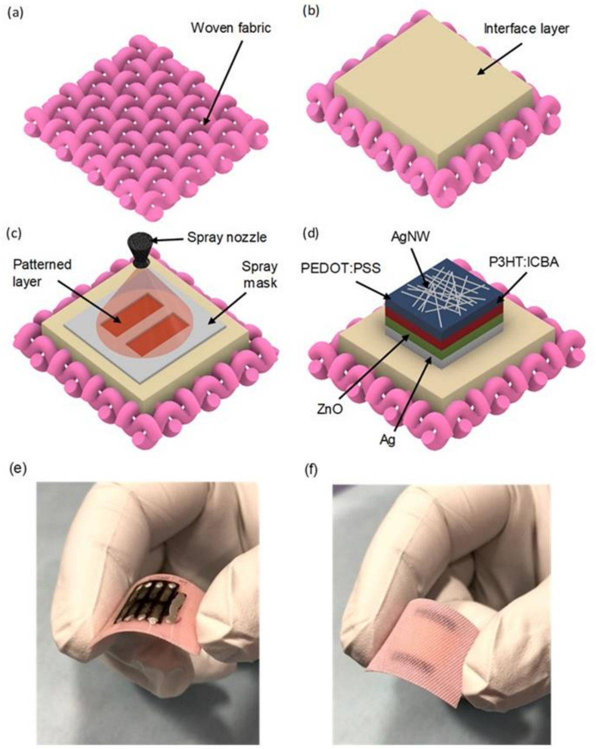

FIGURE 8. **Isometric schematics illustrating the OSC structure and fabrication process. (a) Example woven fabric structure. (b) Screen printed interface layer on the fabric. (c) Spray coating process using a mask. (d) Final OSC on the interface coated fabric. (e) Photo of finished OSC. (f) Photo of underside of textile substrate [221].**

Arumugam et al. carried out extensive research activities on spray coated OSCs on woven polyester cotton [220]–[221]. Figure 8, from that study, shows the key active layer of the poly (3-hexylthiophene) (P3HT) indene-C60 bisadduct (ICBA) (Supplied by Plextronics) formulation [221]. The spray coating provides a repeatable and reliable process capable of depositing thin films onto the substrate. Areas of the fabric where no films are required can be easily masked. The organic solar cells in a prior version of the optimization work achieved 0.02% efficiency on fabric substrates, however the optimized devices [221] have demonstrated an efficiency of 1.23%. The same research group also carried out the encapsulation and durability (bending) study on the spray coated textile solar cells [222].

In the conventional DSSCs architecture, two fluorine-doped tin oxide (FTO) coated glass substrates form a sandwich with a liquid electrolyte in between them.

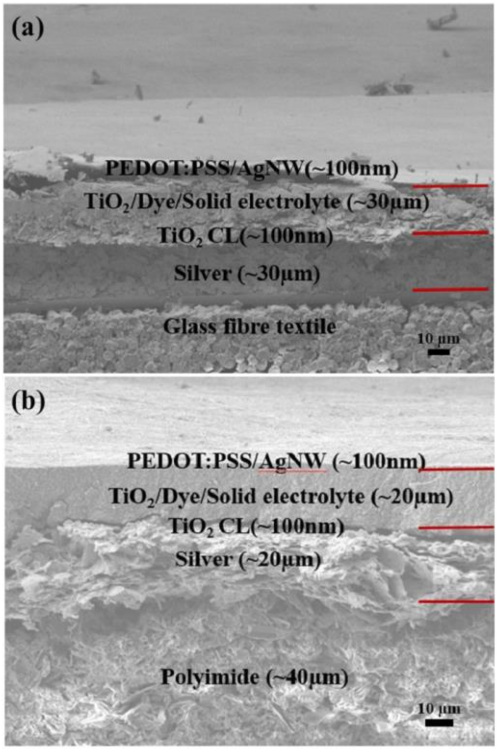

FIGURE 9. **FE-SEM images of (a) Cross sectional view of the printed bare textile ssDSSCs, (b) Cross sectional view of the printed liquid polyimide coated textile ssDSSCs [243].**

Regarding the approaches to the textile DSSCs, one of the two FTO coated glass slides was replaced with conductive fabrics, for example, graphene coated cotton fabrics [223]. The disadvantage of this approach is that, by using the coated fabrics as a stick-on electrode to the FTO glass substrate, the resulting fabric is no longer flexible (and thus not wearable). There are several DSSC designs, including DSSC wires [224]–[226], fibers [203], [227]–[228], metal strings [229], or sewing [230] to create DSSC textiles. Most of these approaches are aimed at the production of single fibers or wires with photovoltaic activity, which are then weaved into textiles [224], [227], [231]–[240]. Unfortunately, studies show that bending cycles significantly disable or degrade the performance of PV fiber [227], [236], [238]. Recently, N. Zhang et al. reported the DSSC textile using a liquid electrolyte fabricated on PBT polymer fibers weaved into different patterns [241]. An efficiency of 1.3% for a single unit of the fiber was achieved, which is the highest reported so far for textile fiber DSSC solar cells [241]. However, it has been difficult for large area applications to connect several crossed, wire-shaped solar cells that had been woven into electronic textiles. Therefore, it remains challenging to weave such wire-shaped solar cells into efficient electronic textiles for practical applications [235].

Liu et al. has extensively investigated printing low temperature processed DSSCs onto woven polyester cotton textiles, achieving efficiencies up to 4.04% [242], [243], [244]. The study is conducted using liquid electrolyte and solid state dye sensitized solar cells (ssDSSCs) on textile substrates using solid electrolytes, such as organic oligomer, 2,2',7,7'-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9'-spirobifluorene, (Sprio-OMetad). The study focused on printing ssDSSCs onto glass fiber textiles, because of the high temperature involved in fabrication of typical DSSCs. The fabric ssDSSCs, as shown in Figure 9(a) [243], demonstrated low efficiency of 4.14×10-6, though the study then optimized the performance of the ssDSSCs on glass fibre textile with flexible PET/ITO, achieving an efficiency of 4.04%. Recently, Liu et al. reported that the textile surface was smoothed out by screen printed aqueous polyimide as the interface layer and then the devices was then directly printed on top, as shown in Figure 9(b); the optimized efficiency has been achieved to 0.4% [243].

3) THERMOELECTRICITY

Thermoelectric devices use the Seebeck effect to convert heat flow to electrical current, and the Peltier effect for the reverse [247]. Thermoelectric devices can be used to harvest body heat to generate electricity to power wearable devices. Classical thermoelectric (TE) devices may be manufactured from bulk [245], [246] or thin film [247], [248] materials, but these devices are inflexible. This makes them unsuitable for use in wearable technology where flexibility is essential. Advances in techniques like inkjet printing and thermal spraying, coupled with the performance enhancements of adapted TE materials and composites (mainly based on polymers), demonstrates the feasibility of TE in wearable technology.

TE textiles have recently progressed considerably [114], [249], [250]. They can be made from TE yarns, fibers, or filaments, which are woven or inserted into fabrics [251]–[257]. Classical textiles can also be coated by TE materials [258], [259]. In the first case, they are mainly based on TE organic polymers, polymer/inorganic semiconductor composites, or organic polymer composites with carbon nanotubes (CNTs) or with graphene as fillers. For the second case, TE materials such as copper iodide, poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) or polyurethane based composites can be used.

Thermoelectric generation

In the Seebeck mode, TE textiles have the great advantage to be able to convert continuously the body heat into electricity, acting as a permanent power supply while the garment is worn. However, due to the low temperature difference between the body and the ambient environment, the power generated is low, typically in the nW range [257]–[259], which is insufficient for wearable applications. An issue with thermoelectrics on humans is generally that the human body likes to conserve heat when it's cold outside. In

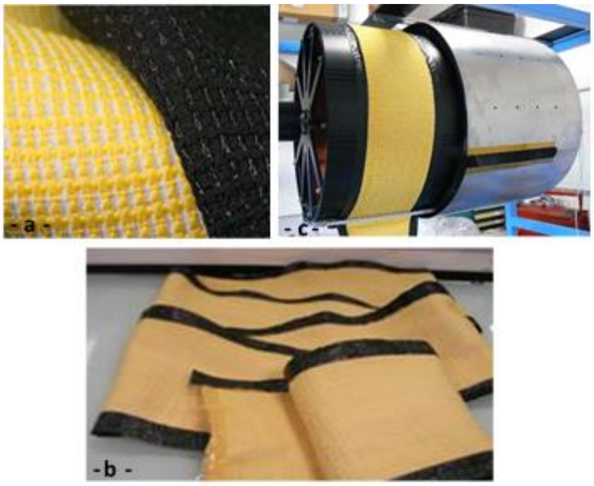

FIGURE 10. – (a) Example of TE textile developed in CEA (b) long band of TE textile and (c) tool used for the TE textile characterization.

this condition, a garment will steal heat from the body to generate energy – user may choose to put a sweater on, which will reduce the temperature differential and defeat the operation of the system. However, the heat dissipated from the human body varies between 100W and 520W depending on body activity [260]. Considering a conversion efficiency of 1% for the TE textile, the generated power would vary between 1W and 5.2W, enough to power many wearable sensors [260]. However, this is unrealistic as covering the whole body with TE textiles is not practical, and a 1% efficiency is tremendously ambitious.

The low power generation results from these factors:

- Polymers have weak TE properties compared to usual Bismuth Telluride (Bi_2Te_3) which is the best TE material at room temperature. Bi_2Te_3 is toxic and therefore unsuitable for wearable applications. Bi_2Te_3 exhibits a figure-of-merit ZT around 1 at 300K while the best polymers present a ZT around 0.4 [261].
- The method of fabrication mandates that binders are added to TE materials during the manufacturing process which degrades the thermoelectric properties of these materials.
- Parasitic thermal resistances between the human body and the environment considerably reduce the heat flow for harvesting.

To explain, the useful power P, generated by a thermoelectric generator is directly proportional to the square of the temperature difference, ΔT_{TE} between the hot and cold sides of the thermoelectric material.

$$P = \frac{V_{OC}^2}{4R} = \frac{\left(N \times S_{np} \times \Delta T_{TE}\right)^2}{4R} \quad (1)$$

Where V_{OC} is the open circuit voltage, R is the total electrical resistance, N is the junction number and S_{np} is the Seebeck coefficient of one junction. To obtain high power, the temperature difference, ΔT_{TE} across thermoelectric materials must be high but this value is significantly controlled by the thermal resistances of the thermoelectric materials. In the ideal case when the thermal resistance is negligible, ΔT_{TE} is equal to the actual temperature difference, ΔT_{ext} so that maximum power is generated and no thermal losses due to parasitic thermal resistances. Practically, this is not the case especially for textile applications where parasitic thermal resistances exist between the human body and environment, the skin and clothes, the clothes and air, etc.). This means that ΔT_{TE} is always lower than the actual temperature difference, ΔT_{ext} between the human body (hot source) and the environment (cold source).

Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) developed e-textiles based on TE [249],[262] as shown in Figure 10a. This technique is compatible with high surface manufacturing (Figure 10b). A dedicated tool has also been developed to characterize these textiles with different convection conditions (Figure 10c). CEA obtained a competitive electrical power around 700 µW/m² for a temperature difference of 7 K. From an industrial point of view, the main advantage is that the textile and the TE device are manufactured in one step, reducing cost. This process results in a large area of TE fabric, supporting flexibility and comfort requirements, and allowing customizable fabric coloration. TE performance of these textiles are preserved after 10 washing cycles.

Thermal management applications

The Peltier mode can be used for localized thermal regulation, switching between cooling and heating behaviors by altering the direction of the electric current. However, a lot of power is required to maintain the temperature difference across the device. Consequently, very few studies consider thermoelectric textiles for thermal regulation, though Hong et al. have developed a flexible thermoelectric cooler which can deliver about 10°C long-term active cooling with high flexibility, mainly thanks to a novel design of double elastomer layers [263].

E-textiles based on TE materials are fast-growing and active research area. They are passive harvesters, requiring no action from the wearer. They propose a high mechanical reliability due to a lack of moving parts, though they do not harvest as much power as other sources, and there is no comprehensive data of durability and repeatability, wash tests, evaluation of costs, reliability, and recyclability, amongst other factors. Most research aims to improve thermoelectric properties of materials, or to improve manufacturing processes. Considerable further work is needed for commercialization.

4) WIRELESS POWER AND RF ENERGY HARVESTING

Wireless power transfer (WPT) and RF energy harvesting represent methods of reliably charging or powering textile-based systems. Different approaches to WPT, using near-field coupling and far-field propagation have been presented for different applications [70]. WPT using Magnetic Resonance (MR) has attracted significant interest due to the improved separation achieved over inductive coupling using the Qi standard [70]. From an e-textile perspective, the coils are the most area consuming component in the system and therefore need to be implemented using textile or flexible conductors. Multiple designs of MR-WPT coils on textile substrates have been proposed [97], [264]–[267]. The key to high efficiency wearable WPT is in achieving high Quality (Q)-factor coils using textile materials [268]. Grabham et al. [265] investigated how different fabrication techniques affect inductance and series resistance of coils. The WPT efficiency of multiple flexible coils fabricated using a rigid PCB, flexible PCB, and conductive fabric are been investigated in [265], showing around 20% lower WPT efficiency using the conductive textile coils compared to the flexible PCB. Figure 11 shows textile-based MR WPT coils fabricated using different techniques.

Considering MR-WPT in proximity of the body, the SAR limit remains the key regulation to adhere to regarding the user's safety. For example, the 6.78 MHz WPT textiles utilized for through-hand WPT in [97] achieve a SAR of 0.103 W/kg for 1 gm normalization sample, over 15 times lower than the 1.6 W/kg regulatory limit. Similar absorption levels below 0.5 W/kg were reported in [269] using flat conductive textiles. From [97] and [267], MR-WPT using textile and flexible coils can achieve high efficiencies enabling wireless-powered e-textiles. Future work and challenges include a detailed investigation of the reliability of coils and e-textile WPT systems, as well as the integration with other textile-based components to realize battery-free e-textiles.

Rectennas (antennas with rectifiers) are needed for WPT and RF-EH systems to power e-textiles, where rectenna design is driven by similar metrics as antenna design [270]. Rectifiers have been incorporated on textile substrates [73],[271]. In addition, [272] addressed the integration of active microwave components such as power amplifiers and their reliability, showing less than 0.5 dB discrepancy compared to solid copper. To ensure reliability and bending resistance of the mounted discrete components, the Schottky diodes, and any matching lumped elements, encapsulation using glob-top epoxy [273] or vacuum forming is required [17]. To overcome the lossy dielectric properties of the textile, [79] integrates a rectifier on a low-loss substrate with a textile patch antenna. While such approaches guarantee optimal rectifier performance, it requires a low-loss and reliable textile-to-PCB transition. Furthermore, considering the integration in clothing, certain dielectrics may require special waste handling techniques as opposed to copper threads or electro-plated fabrics which can be directly

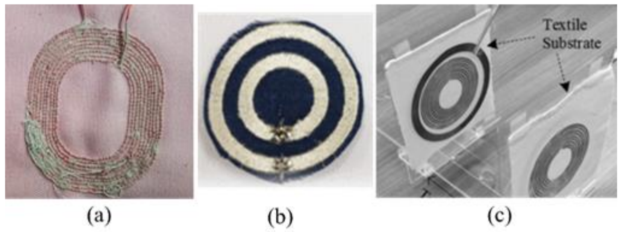

FIGURE 11. Textile-based MR-WPT coils: (a) embroidered coils using Litz-wire threads [97], (b) conductive fabric coils [267], (c) adhered copper foil on textile [266].

recycled. Improvements to packaging of rectennas have been proposed in [84], presenting a rectifier integrated with the antenna filament which can be woven in the fabric [17]. A flexible rectenna filament concealed in textiles and fabricated using the technique in [19] has been demonstrated in [274], charging a textile-supercapacitor to 4 mJ in 30 seconds on the body from a 16.6 μW/cm^2 RF power density, showing the highest end-to-end charging efficiency compared to textile and rigid rectennas, as well as other textile energy harvesters.

Enabling fully-textile rectennas and RF power supplies is limited by the ability of creating high efficiency rectifiers on textile substrates. However, recent work has shown textile-based rectifiers with efficiencies surpassing their rigid counterparts [119]. Reliable textile-based rectennas must trade off the infrequency of insertion losses on textile-substrates while achieving a good impedance match. Outstanding challenges lie in the reliability of e-textile rectennas and their integration within e-textile systems.

4) ENERGY STORAGE

Batteries are standard power supplies for portable devices. However, when attached to textiles, traditional batteries significantly alter the property of the textiles because of their inflexibility. Current flexible batteries, while superior in this regard, do not bend or flex like textiles. Hence, the following energy storage technologies are evaluated.

Power supply on textile to the e-textiles applications remains a significant challenge and a key limitation for the practical applications towards the commercialization of the energy harvesting systems. Integrating power supply modules inside textile products has implications for health and safety, long-term stability, shelf life, inflexibility, washability, replacement, recharging and environmental sustainability concerns.

Conventional approaches to deliver power supply of e-textile applications are to use standard commercially available capacitors and batteries, for example, super capacitors, coin cell [275] and AA/AAA batteries [276]. However, these off-the-shelf power supplies are typically rigid, bulky and are incompatible to remain or maximize the texture of the fabrics, at the same time, restricting the flexibility and breathability of the garment and being obtrusive for the wearer [37]. Research activities exploring the integration of energy storage into the textile include both flexible textile supercapacitors [132], [277] and flexible textile batteries [278], [279]. Both of the above approaches can be incorporated into the textile or built up on the fabric surface to provide energy storage capacity while maintaining the textile properties. However, the self-discharge of these devices and the incorporation of liquid and gel aqueous electrolyte remain a challenge for the practical, safety and sustainable deployment of e-textiles.

Supercapacitors are electrochemical energy storage devices that have several advantages over secondary batteries such as fast charging time, higher power density and cycling stability, environmental friendliness, flexibility, and ease of integration into textiles [280]. In e-textiles, supercapacitors can be an alternative to the battery or to supplement the power output of the battery to other electrical components in the e-textile system, or to act as energy reservoirs for energy harvesters [281]. Textile supercapacitors share the same structure as conventional electrostatic capacitors. A supercapacitor can be created by sandwiching a layer or piece separator containing an electrolyte by two layers of porous electrodes. These material layers can be implemented with textile materials to form a flexible device for powering or buffering e-textile systems.

Depending on the energy storage mechanism, supercapacitors are categorized either as electric double layer capacitors (EDLC), pseudocapacitors, or capacitors that hybridize both approaches [282]. In e-textiles EDLCs are more reliable than pseudocapacitors, as they can be created with non-hazardous materials including flexible carbon, metal-framework and conductive polymer coated/embodied textile electrodes with non-hazardous electrolyte. However, a pseudocapacitor requires potentially hazardous materials, like manganese (IV) oxide, to store electrical energy through a redox reaction. Previously hazardous substances, such as strong acids or alkalines [283] in the electrolyte, or corrosive oxide materials [284] in the electrode, were used to realise textile supercapacitors. However, the supercapacitor required an additional packaging material to limit the possibility of skin irritation on a user.

Cheng et al. [285] implemented a textile-based supercapacitor with nickel-metal-framework, with a reduced graphene oxide as textile electrode. The supercapacitors were tested with a high concentrated alkaline solution as an electrolyte and achieved an area capacitance of 95 mF/cm^2. Nie et al. [286] fabricated a fibre-shaped supercapacitor with graphene oxide, poly(pyrrole) and poly (lactic acid) filament fibre electrodes. A high area capacitance of 158.8 mF/cm^2 was achieved by the flexible supercapacitor using a phosphoric acid gel electrolyte. In both cases, the aqueous electrolyte contains hazardous materials, limited operating voltage of less than 1 Volt, and expansive carbonized materials. Yong et al. [287] achieved a flexible supercapacitor integrated in a single piece of polyester-cotton textile. Both electrodes were fabricated via spray coats on an inexpensive carbon material on both side of the same textile, and the electrolyte was made with slightly acidic organic electrolyte with polymer network acting as a separator. The textile supercapacitor was also encapsulated with a hot melt polymer film, achieving an area capacitance of 20.6 mF/cm^2 and electrochemical stability between ±2.8 V.

Textile supercapacitors are a novel way of storing electrical energy in e-textile system. To date, e-textile supercapacitors have received considerable attention, notably in the areas of electrode/electrolyte material selection, device structure and designs (including symmetric and asymmetric configurations) and encapsulation methods. However, numerous issues must be addressed before commercialization. The wettability between the electrode and electrolyte interface must improve while electrolyte properties, including ionic conductivity and volatility must be optimized to enhance the electrochemical performance of textile supercapacitors. Methods for evaluating the electrochemical performance and mechanical flexibility under different operating conditions are required to understand the trade-off between the mechanical properties and electrochemical performance of the supercapacitor against other physical demands of textiles such as abrasion, bending and washing.

Textile battery research started with the primary battery on textile substrate. However, research in this topic remains limited, due to the technical obstacles of matching the physical properties of functional materials with textile's properties such as high surface roughness, porosity and low processing temperature. In 2012, Gaikwad et al. [288] reported the primary battery fabricated using conductive silver fabric, coated with magnesium oxide and zinc. The whole battery including liquid electrolyte was completely sealed by an elastomeric casing. It achieves potential of 1.5 V. The first primary batteries realized on a standard woven textile substrate were reported in 2015 [289]. Liu et al. [289] reported a liquid activated textile battery, achieving potential of 1.3 V, which could be used for the detection of aqueous liquid, powering an LED upon detection. It was fabricated by stacking up several dip coated textile layers. In 2019, Li et al. [290] reported the advance of built in membrane into the standard woven textile for the primary textile battery, achieving potential of 1.18 V.

The secondary textile battery has also been reported, along the research on the primary textile battery. However, the achievement in the second textile battery remains limited. Hoon ha et al. [291] demonstrated a rechargeable lithium ion battery (LIB) using lithium titanite oxide (LTO) and lithium iron phosphate with reduce graphene oxide coated conductive carbon fabric to form the flexible anode and cathode respectively. The LIB was tested in an aluminum film pouch with a commercially available separator and lithium bis (trifluoromethanesulfonyl) imide electrolyte. The textile battery survived after 1000 bending cycles and achieved an area capacity of 1.2 mAh/cm^2 at 388 $\mu A/cm^2$ discharge current between 2.5 and 0.5 V (based on a high loading of cathode material of 8 mg/cm^2). Huang et al. [279] implemented a flexible quasi-solid-state zinc ion battery (ZIB) with two layers carbon cloth contained zinc and manganese dioxide (MnO_2) with reduce graphene oxide coating as anode and cathode. The flexible ZIB was assembled and tested in an open-air environment with a rice paper separator and a zinc sulfate/manganese sulfate aqueous electrolyte. This demonstrated an area capacity of 5.1 mAh/cm^2 at a discharge current of 2.6 mA/cm^2 (based on a high mass loading of MnO_2 of 17.75 mg/cm^2). In both cases, the batteries were assembled with multiple fabric layers, using specially engineered textiles and include a discrete filter paper layer as separator. Yong et al. [132] reported a flexible ZIB fabricated in a single polyester cotton layer, both anode (Zinc) and cathode (MnO_2) with carbon conductive additive were spray coated onto the textile contained a polymer separator. The flexible encapsulated textile ZIB demonstrated the area capacity of 6.46 µAh/cm^2 at 0.5 mA/cm^2 discharge current between 1.8 V and 1 V (based on a loading of MnO_2 of 1.27 mg/cm^2).

Future research in textile batteries should focus on functional material formulations, packaging and management systems for performance optimization. The material formulations should allow the deposition of energy materials onto the textile surface, or into the textile structure. These formulations will need to support the low temperatures required for processing, and be environmentally friendly, non-toxic and be constructed from high energy density materials. Battery packaging on textiles is another significant challenge, as the battery must be properly sealed on or within the textile structure to maintain the structure of the battery, and to avoid leakage of functional materials into the environment.

V. DISCUSSIONS AND CONCLUSIONS

This paper reviewed the state-of-the-art challenges and progress in the manufacture, performance and powering of a broad range of e-textile devices. Despite the steady supply of prototype devices, the reliable combination of textiles and electronic properties into a market viable e-textile garment remains a key challenge for e-textile manufacturing.

Currently, e-textile manufacture is based on functionalizing a 1-D textile/plastic yarn or a 2-D textile substrate. In both approaches, scalable industrial textile processes such as weaving, embroidery and screen printing have been employed but the implemented electronic materials show varied degree of durability when exposed to practical stresses such as washing and bending after fabrication. Printed integration of electronic functionality on textiles degrade quicker than woven integration of conductive threads and yarns when exposed to these stresses. Better integration and mechanical robustness are shown with the woven integration of electronic filament circuits into textiles. Unlike the other approaches, this technology offers the flexibility of exposing or concealing the electronic functionality within the textile. It is also currently the most promising technique, but because it is unconventional, there is no dedicated automated mechanism for inserting these electronic filaments. Textile machinery manufacturers would need to adapt their equipment and incorporate automated filament feeders to enable e-textile garment manufacturing in this way.

Advances in the fabrication of power supplies and storages for e-textiles application are evident but the majority of the current solutions are still limited by low power outputs and durability. For energy harvesting solutions, typical power outputs are suitable for sensing applications. Wireless power transfer textile and flexible coils can provide power at efficiencies up to 90% which is enough for e-textile devices, detailed research on coil reliability and coil integration with textile-based energy storages are still necessary to ensure battery-free implementation. Textile based batteries are a potential power source for e-textiles, however textile and bio-compatible functional materials that enable high energy density at low processing temperatures are still needed. In general, these energy technologies must be optimized for increased power outputs while meeting the requirements for wearability and durability in e-textile applications.

Research into e-textile manufacture has largely focused on integration of electronic materials into the textile. Limited research exists on the recyclability of e-textiles to allow a sustainable circular economy [292]. The current standard, IPC-8921, that was finalized by the IPC D-72 E-Textiles Materials Subcommittee only gives requirements for conductive fibers and conductive yarns, including standardized key characteristics, durability testing, and industry test methods [293]. Implementation of standards that provide guidance on the use of safe, biodegradable and disposable electronic materials on the textile is necessary. This is especially important for some e-textile devices such as textile batteries that may require some potentially hazardous materials to achieve desired electrical performance.

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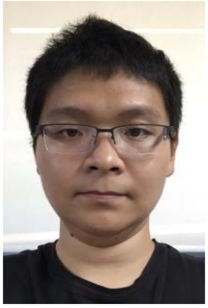

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