CHAPTER 8

Fiber-Based Sensors: Enabling Next-Generation Ubiquitous Textile Systems

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8.1 Introduction

Wearable electronic systems for health monitoring can take many different forms ranging from common commercial wrist-worn systems, to more advanced wireless bandages, socks, and fitness shirts. Some major advantages of integrating sensors and actuators directly into body-worn textiles rather than as separate wearable entities are enhanced comfort, and larger sensing area [1,2]. Textiles with integrated sensing capabilities could significantly improve healthcare monitoring in remote or harsh locations, where data sensed across the surface of the entire body could help to quickly identify problems. Such embedded ubiquitous sensors could provide novel insights and correlations between healthcare parameters measured from the textile and additional body-worn environmental or health sensors. Textiles used in spacesuits, extreme cold weather clothing [3], and military uniforms [4] can be outfitted with sensing fibers to simultaneously detect events, such as blunt force impact, excessive bleeding, and abnormal heart rates. The additional spatial information provided by arrays of sensing fibers could indicate not only the occurrence of such events, but also where they occur on the body and to what extent.

In this chapter, we examine the challenges to textile integration of sensors, the requirements for integrated sensors, and potential fiber-based sensing modalities. Although we emphasize the health applications as a motivator of this article, our discussions can be extended to other applications, such as environmental monitoring and energy harvesting. We also discuss briefly some of the methods of sensing fiber production from benchtop prototyping to large-scale production, and examine how fiber-based sensors can be integrated in textiles with corresponding sensing circuitry.

Wearable Technology in Medicine and Health Care.
DOI: https://doi.org/10.1016/B978-0-12-811810-8.00008-7

8.2 Conventional Textile Wearable Integration Techniques

Textile fabrics consist of a hierarchical structure, which incorporates building blocks (most commonly fibers/yarns) of different sizes and scales through combinations of many processing steps, resulting in structures that can exhibit unique physical and mechanical properties. Fig. 8.1 shows different hierarchical levels within textiles, which may be engineered to enable sensing. The fibers are made of polymers or macromolecules. During the process of fiber manufacture, these macromolecules are arranged in a fibrillar structure consisting of crystalline and noncrystalline phases, producing a structure of high aspect ratio and with diameters (or equivalent dimension) ranging from nanometers to microns [5]. Continuous and discrete lengths of these fibers are subsequently assembled into yarns with dimensions in the range of hundreds of microns. The yarns are then combined in a fabric structure (woven, knitted, etc.) to produce textile fabrics. Needless to say, fabrics can also be manufactured directly from fibers through the nonwovens processes. Desirable properties for a given application can be enhanced or engendered in a textile fabric at any of the hierarchical levels (molecule, fiber, yarn, etc.). Most of the work done to produce electronic textiles, or e-textiles, has focused on altering the electrical properties of the bulk textile fabrics or the yarns in order to create textiles capable of sensing and signal transmission [2,6]. While some of these methods are advantageous, they have not made the necessary transition into commercial applications, primarily because they require multiple additional processing steps [7]. Arguably, the next-generation e-textiles will consist of fibers which are designed to perform sensing and actuation functions, and which can be produced using standard textile production techniques [8]. The methods described here explain the more conventional methods of e-textile integration.

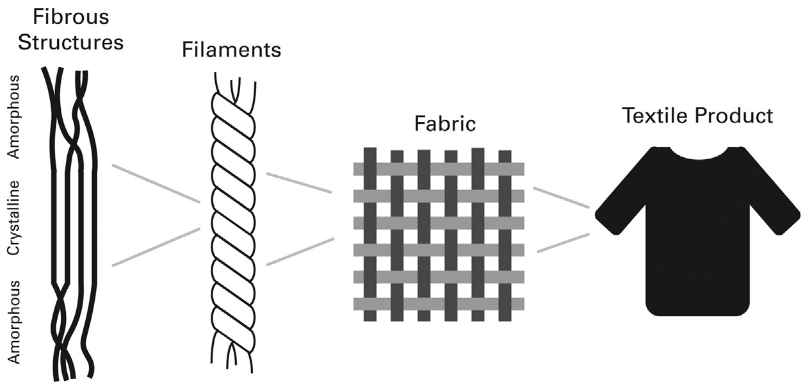

Figure 8.1
"Textile structures are enabled by hierarchical integration of components ranging in size from nanometer scale fiber structures, to macroscale textile products."

8.2.1 Rigid Component Integration

The earliest sensing textile systems consisted of rigid commercial off the shelf (COTS) components integrated into textiles using methods, such as sewing to affix the sensor and corresponding electronics within the textile [6]. In many examples of integrating rigid components, conductive fibers/yarns are used as interconnects to both sew components in place and provide an electrical connection to other rigid components. Similar sewing techniques have been used to incorporate sensors fabricated on flexible polymeric substrates into textiles [9,10]. For example, temperature and humidity sensors developed on polyimide have been sewn into woven textiles and shown to have a stable response [11]. While this form of integration functions well for prototyping and demonstrations, it does not translate well to commercial applications because it fails to address issues such as processability and comfort.

8.2.2 Printing

Printing methods, including screen and inkjet printing have been used to print necessary conductive material directly onto textile surfaces [12,13]. Because screen printing is already frequently used for textile production, it provides a potential avenue for commercial e-textile production. Printed conductors can enable flexible and conformal sensors and interconnects; however, these systems suffer from size limitations because smaller printed conductors produce higher electrical resistance. This is due, in part, to the porosity of the fabrics onto which these materials are generally printed. Stability of these printed conductive lines is also susceptible to repeated bending/stretching of the substrate fabric and long-term use may be limited [14]. Screen printed conductive pastes based on silver/silver chloride are most commonly used. These materials can be printed as both electrodes and interconnects, and can adequately bend and stretch along with the textile substrates they are printed on. Novel printable inks consisting of carbonaceous and silver nanomaterials may enable improvements in printed conductor/sensor quality. An advantage of producing printed e-textiles is that sensor sizes and geometries can be tailored for different applications. For example, subsequent layers can be printed onto the Ag/AgCl inks to enable potentiometric ion sensing [15,16] or to functionalize the electrode surface for biopotential sensing.

8.2.3 Conductive Yarns/Fibers

Highly conductive yarns also provide promise in enabling e-textiles, particularly as textile-embedded interconnects. Conductive yarns have been developed with conductivities ranging from 5 Ω/m to several kΩ/m [1]. The conductive filaments/yarns with the best electrical properties are comprised in whole or in part of metallic fibers, with stainless steel being the most commonly used material. These conductive yarns are generally not insulated, and instead must be packaged in textiles such that they are only exposed in the desired areas. These yarns have been woven to form large electrodes which can measure biopotentials [17], sense strain [18], or detect touch events [19]. Google's Project Jacquard is an example of a commercial effort aiming to produce such yarns for use in textile-embedded touch interfaces for controlling external devices.

8.3 Textile Requirements for Integrated Sensors

Many flexible, conformal sensors have been developed for textile integration; however, the planar geometry of these sensors often requires them to have a large active surface area. These sensors often have a low aspect ratio (length approximately equal to width), which is less suitable for fiber-based integration. Initial design of sensors with a geometry mimicking that of traditional textile systems, has produced promising results, indicating that multiple types of sensors can be scaled to have a high aspect ratio (length much greater than width) making them suitable candidates for fiber-based sensing. Fiber-based sensors designed to be embedded in textiles, will generally be incorporated in conjunction with conventional textile fibers. Conventional textile fibers can include natural fibers, such as cotton and wool, or synthetic fibers, such as polyesters and nylons. The mechanical properties of these fibers can vary significantly, and ideal fiber-based sensors should closely match the mechanical and physical properties of the textiles. Additionally, stretching and flexing should not cause changes in the sensor output (unless desired, as in strain sensors).

8.4 Spatial Sensing using Fiber-Based Sensors

The advantage of incorporating fiber-based sensors into a wearable system, is that these sensors can be easily routed to or integrated at different locations within the textile. Fiber-based sensors can either be independent, meaning that a single fiber can perform some sensing capability, or dependent, meaning that the fiber works in conjunction with another fiber or system to enable sensing. Of the sensing modes described, strain, biopotential, and temperature sensing generally represent independent fiber-based sensing modes, whereas pressure and wetness represent dependent sensing modes. The independent modes normally sense across the entire length of the fiber, such as in the strain sensing mode, where the resistive response of the entire length of the fiber will be used to determine strain levels. Such independent sensing fibers are advantageous because they require fewer signal transmission channels, and thus fewer interconnects, however, they are limited in their spatial sensing capabilities. For example, a fiber may only be strained along a small portion of the entire fiber length, but resistive sensing will not provide us with any information about the location of strain, or what percent of the total fiber length is being strained. This limitation should be accounted for when deciding how to integrate the fibers into a sensing fabric. Textile knitting and weaving methods could be used to enable or restrict fiber straining in certain portions of a larger sensing fabric as shown in Fig. 8.2. It is important to note that for most wearable applications of sensing fibers, it is not necessary to have extremely high-density of sensing fibers.

Additionally, array-based sensors are preferred to help increase the accuracy and redundancy of the sensed information if the information coming from multiple sensing points is averaged. To resolve data from such sensor configurations, a multiplexing circuit is most commonly used. This circuit allows for the circuitry to select each sensor individually in order to retrieve the data from the array one sensor at a time. A fast sweep through the array of all sensing points within the textile allows for the necessary sampling rate of the full array to be reached.

8.5 Fiber-Based Sensing Modalities

Multiple sensing modalities could be enabled in textile applications using fiber-based sensors. The sensing mechanisms described here exhibit methods that could be enabled by tuning conventional textile production methods. Most of the fiber sensors described here also incorporate a limited number of different materials into the fiber cross-section designs. Other more complex fiber-based sensing structures could be explored for biochemical sensing and gas sensing. Also, though fiber-based sensors are discussed here, other components that could be useful in wearable textile systems could also be built directly into fibrous structures. These include fiber-based energy harvesters, super capacitors, antennas, and batteries [8,20].

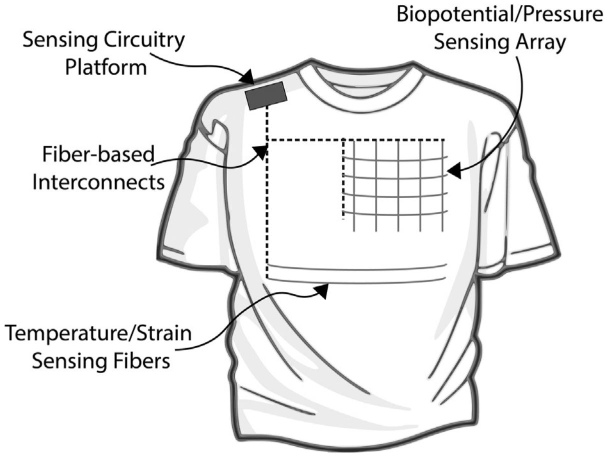

Figure 8.2
"Sensing textiles may include different component sensing fibers at different locations for highly customized healthcare sensing applications."

8.5.1 Pressure Sensing

Pressure sensing using fibers can be done in multiple configurations. If capacitive pressure sensing alone is desired from the fibers, then a conductor can be entirely encapsulated within the fiber itself, as in Fig. 8.3A. Using this configuration, the point where two fibers cross perpendicular to one another will act as the sensing location with the insulating material used to coat the fiber serving as the capacitor dielectric medium. The material properties of the insulating material, particularly its elastic modulus, will determine the amount of compression the fibers undergo when pressure is applied. As compression occurs, the proximity of the crossing conductors will be increased and the resultant capacitance will increase. Fibers for this type of sensing could also be designed such that the conducting segment of the fibers is exposed, with air acting as the dielectric [21]. If this configuration is used, the fibers may be simultaneously capable of other impedance-based sensing modalities. Highly-sensitive fiber-based capacitive pressure sensors have already been developed for textile systems [22]. These systems show promise for monitoring breathing rates, taking ballistocardiogram measurements, detecting impact, and as a user interface using touch-based input.

8.5.2 Wetness Detection

By either fully exposing portions of the fiber conductive segments or by using a porous insulating material, the presence of certain fluids within a textile could be detected via impedance measurements [23,24]. Many biological fluids of relevant interest for health monitoring contain relatively high concentrations of ions, which enables fluid detection using impedance-based methods. When an ionic fluid is present in the space where two sensing fibers crossover one another, the electrical impedance will be orders of

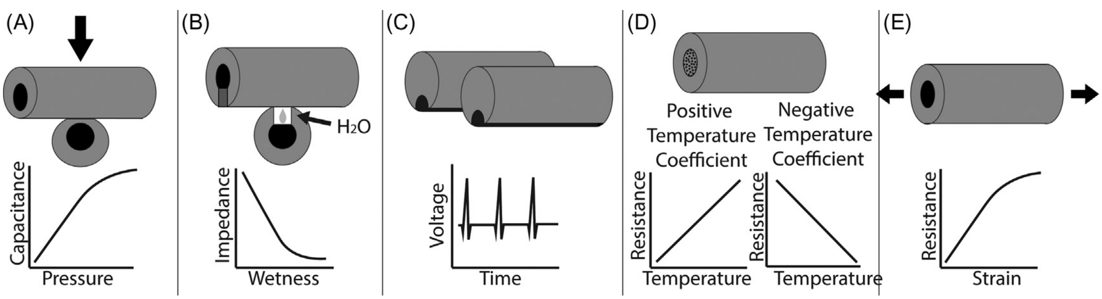

Figure 8.3
Potential embodiments of fiber-based sensors/sensing modalities using multicomponent fibers. (A) Pressure sensing; (B) wetness detection; (C) biopotential recording; (D) temperature sensing; and (E) strain sensing.

magnitude lower, compared to the impedance when no fluid is present (due to the high impedance of air). An example of wetness detection using multicomponent fibers as shown in Fig. 8.3B.

Fibers capable of detecting wetness could be used to detect the location and extent of bleeding, sweating, and urination. More specific information about the salinity of the fluid that is penetrating the sensor could potentially be extracted if the fibers are designed such that a controlled amount of fluid enters each sensing crossover point. Choice of fiber materials and geometric designs can either aid or inhibit the uptake of fluid into the fiber crossover point. For example, more hydrophilic and/or wettable fiber material surfaces will more readily carry the fluid into the crossover point. The high aspect ratio of fibers enables them to be designed to promote capillary action, which also increases fluid uptake into the sensing crossover point. Fibers designed for multimodal sensing, cannot simultaneously perform both capacitive and impedance-based sensing functions when the fluid is present between the two conductors because the fluid will render the capacitive sensing mode inaccurate.

8.5.3 Biopotential Monitoring

Biopotential recordings using textile electrodes have been a major focus of research and development. The use of conductive yarns to produce macroelectrodes capable of monitoring heart rate and generating electrocardiogram waveforms has been reported by numerous researchers. In order to obtain adequate biopotential signals, intimate skin-electrode contact is required [25]. Appropriate textile integration techniques that help bring the electrode fibers close to the skin surface can help ensure functional sensing if the fibers are to be used as dry electrodes. Dry electrodes are desired for textile sensing systems, since repeated application of electrode gel or moisturizer is not practical for long-term and repeated recording [26]. Poor electrode interfacing can lead to an increase in contact impedance at the skin-electrode interface, leading to poor signal recordings. Biopotential recordings require at least two conductive fiber segments to be in contact with the skin, in a configuration as shown in Fig. 8.3C. A major challenge to recording biopotentials using fiber-based sensors is the inherent impedance of small fibers. As fiber size is reduced to produce sensors that mimic common textile fibers, the reduced conductor cross-section leads to an increase in the conducting fiber resistivity. This challenge is exacerbated because of the need for conductors with flexible, textile-like properties. The incorporation of conductive materials with polymeric materials to produce conductive fiber segments, results in fibers that are inherently more resistive than metallic conductors. Fibers with increased resistivity are more susceptible to electrical noise, especially when attempting to record and amplify biopotential signals with amplitudes on the order of millivolts.

8.5.4 Temperature Sensing

Body temperature is a clinically relevant healthcare parameter frequently used to aid diagnosis of both short-term and chronic illnesses. Carbonaceous polymer composites can be tailored to have thermistive properties, which enables them to be used for temperature sensing applications. Temperature sensing fibers using thermistive polymers, can comprise either positive temperature coefficient materials (resistance increases due to rising temperature) or negative temperature coefficient materials (resistance decreases due to rising temperature) as shown in Fig. 8.3D [27]. Temperature sensing fibers function in the independent sensing mode, because they do not require interaction between multiple fibers. If the entire length of the fiber is comprised of the thermistive material, the length of the fiber will sense changes in temperature. However, if temperature sensing is desired at a particular location, the fiber could be functionalized with thermistive material only at that location, with other nonthermistive conductive polymers incorporated for interconnection throughout the length of the polymer. A challenge to fabric integration of temperature sensing fibers is that impedance-based sensing using independent fibers requires electrical connections at both ends of the fiber. In applications, where multiple fiber sensing types are to be incorporated into a textile fabric, dedicated temperature sensing fibers may also be incorporated to compensate the measured impedances of other sensing fibers to changes in temperature.

8.5.5 Strain Sensing

Another parameter that can be measured using fibers is strain. Wearable strain sensors can be used to monitor breathing and motion. Conductive polymers can be tuned to exhibit piezoresistive properties, such that in-plane strains along the length of the conductor induce an increase in impedance. Both integrated yarns [28,29], as well as monofilament fibers [30] incorporating carbonaceous conductors have been developed for textile integrated piezoresistive strain sensing. Methods of coating elastomeric fibers with carbon, or combining carbon with thermoelastic polymers have been used to produce the conductive portions of yarns and fibers [31]. Strain sensors for wearable applications should function for lower strain regimes, and few wearable applications require fibers capable of being strained more than 30%. Carbon-based conductors experience a degradation of mechanical strength as carbon is added, so lower levels of carbon are also generally preferred [32]. Polymer-based conductive composites containing a percolating network of carbonaceous materials, such as carbon-black and carbon nanotubes have been used to create piezoresistive strain sensing fibers. Fibers for strain sensing ideally exhibit a linear resistive response to increasing strain, are not susceptible to changes in environmental temperature and humidity, and should exhibit little hysteresis following mechanical cycling [33]. As such, it is best to encapsulate the conductive portion of the fiber using an insulating polymer for both sensor stability and mechanical support as shown in Fig. 8.3E. Much strain sensing fiber research has found sensing yarns and fibers to suffer from nonlinearities due to the geometric irregularities, and sensor degradation due to repeated washing and folding. Further research is needed using new materials and fabrication methods, to address some of these problems.

8.5.6 Fiber-Optic Sensors

Fiber-optic sensors have found some utility in textile sensing systems for sensing strain and fiber bending. Small-scale fiber-optic systems are inherently suitable for textile integration because they can have outer fiber diameters of 300 μm or less. They also have advantages over the aforementioned sensing fiber types because of their electromagnetic immunity [34,35]. Fiber-optic sensors consist of a core material and a cladding material with differing refractive indices which enable sensing based on analysis of the light that is either reflected back to the emitting end of the fiber or transmitted to the end of the fiber. There are two primary types of fiber-optic sensors, which are commonly used in textile applications. Fiber Bragg grating sensors are optical sensors, which consist of a short section of periodic alternating core segments of differing refractive indices. These differences in refractive indices cause a shift in the frequencies of the reflected light in response to changes in either temperature or pressure [34]. Because the reflected light is measured at the emitter, these fibers do not require connections at both fiber ends in a textile application. The second common type of fiber-optic sensors are intensiometric sensing fibers, which measure the intensity of light at the optical fiber outlet. These fibers function by modulating the intensity of input light, and examining output intensity. For fibers where microbending is present, some of the light will be dispersed before reaching the end of the fiber so light intensity will be diminished [34]. Intensiometric sensing also enables sensing of both pressure and temperature. Fiber-optic sensors can be used to measure important physiological parameters such as heartbeat and respiratory rate [36].

8.6 Fiber Sensor Prototypes

8.6.1 Microfabricated Fibers

Highly flexible, microfabricated sensors with a high aspect ratio have been demonstrated to mimic textile fibers [37]. These microfabricated sensors were fabricated as planar devices, each consisting of an H-shaped cross-section with the conductive components located in the middle of the cross-section. When a second set of these devices is placed on top of and perpendicular to the first set, the points where the fibers crossover one another, enable multiple modes of sensing. These microfabricated sensors have been fabricated using gold as the conductive segment, and a flexible polyimide material as the insulating component. The production cost per device of these microfabricated fiber sensors is much higher than other fiber sensors, but may be suitable for high technology applications where sensor precision and stability is of great importance. Microfabricated fibers can contain biocompatible precious metal conductors such as gold, platinum, and silver as the conducting component, thus enabling low fiber resistance and lower sensor noise susceptibility.

8.6.2 Paper-Based Fibers

Low-cost sensing alternatives are desired for some clinical healthcare settings, such as remote health clinics in rural locations, or for at home short-term monitoring. In these settings, disposable, yet readily available materials could be used to produce sensors. Materials such as paper can serve as a low-cost sensing substrate, which can be processed using inexpensive rapid prototyping techniques. Paper also can be used for chemical and biological sensing, where contact with bodily fluids requires subsequent incineration of sensor materials [38,39]. By combining printing and cutting techniques, low-cost sensors which mimic fibers have been produced for multimodal sensing. An advantage of using this method is that paper-folding techniques (such as folding/origami) can be used to quickly enable novel sensing modalities [40]. A foldable, three-layer fiber sensing patch was produced using conventional screen printing and laser cutting techniques, which was capable of pressure sensing, wetness detection, and biopotential recordings [41]. For these sensors, a silver/silver chloride paste was printed on filter paper to form the conductive portion of the sensor, with subsequent layers of a flexible insulating material screen printed on the substrate, leaving only a small segment of the sensing traces exposed. In addition to printing the conductive lines to form fiber sensors, interconnects were also printed on the paper to connect these fibers to external sensing circuitry. The printed interconnects are encapsulated by the printed insulating paste, so that they are less susceptible to interference. Because paper substrates are capable of quickly absorbing moisture, the substrate should be well insulated in all places except where sensing is desired. Interference could occur if moisture penetrates the paper, enabling potential electrical short circuits between neighboring or overlapping conductive traces. Additionally, the conductive interconnects should be well insulated to prevent electrical short circuits between stacked layers when the sensor is folded. Laser cutting and folding lines were used to enable perpendicular alignment of the paper-based sensing fibers when the sensor is folded. The location where two sensing fibers crossover was evaluated for capacitive response to application of force in the range of general human touch. This disposable sensor exhibited pressure sensing capabilities, wetness detection, and biopotential recordings.

8.6.3 Printed Fibers

Though 3D printing is not a conventional textile fabrication method, it has gained great interest in recent years for its versatility in printing objects of all shapes, sizes, and materials including conductive materials [42]. Conductive polymeric materials for 3D printing have been developed and commercialized. Both liquid and solid conductive filaments have been used to 3D print conductive fiber structures. Using liquid deposition modeling, conductive nanoparticles have been dispersed in common 3D printable plastics such as poly(lactic acid) (PLA) using high volatility solvents [43]. Liquid deposition methods might allow the integration of other functional nanofillers (i.e., graphene [44]) into printable filaments, which could enable sensing modalities beyond those afforded by conducting filaments alone. Challenges when using liquid-phase filament materials arise from the rheological properties of the material, which can be compensated for by the extrusion nozzle geometry and the shear rate at the nozzle during extrusion. These parameters must be characterized in order to tune the print flow settings to achieve the desired printed material dimensions, such that printing multiple materials simultaneously may be challenging. While solid filament materials can also be embedded with conducting particles, they are generally used to produce more rigid printed materials, making them less suitable for textile applications where soft, flexible fibers are desired. Printing of soft, flexible sensing fibers with an appropriately shaped cross-section has been demonstrated to produce multimodal sensing fibers [21]. A challenge to producing printed fiber sensors is the printable resolution of each component in multicomponent fibers, but this may be improved as new filament materials and new printing systems are developed. Using multifilament 3D printing techniques, both conductive polymers and insulating polymers can be simultaneously printed to form complex structures. Printing techniques can be used to print macroscale polymer-based textiles or fabrics, with sensing components/fibers printed simultaneously within the textile itself. A 3D printed woven mesh structure that mimics textiles comprised entirely of conducting material has been printed using liquid deposition techniques [43]. Methods for producing similar printed fabrics have also been developed using conventional inkjet printing techniques [45]. These examples of printing textile substrates could enable novel woven sensor geometries for multiple applications.

8.7 Large-Scale Fiber Production

One of the major barriers to large-scale commercial production of sensing textile fibers is the fabrication of such fibers using conventional textile fiber production methods. Polymeric fibers for textile applications are generally produced using fiber spinning methods such as melt spinning, solution spinning, and reaction spinning. Of these, melt spinning is the most promising method of fabricating multifilament sensing fibers with unique cross-sectional geometries or multiple component filaments. Solution spinning and reaction spinning may be used to produce monofilament material sensing fibers using certain polymers depending on the desired sensing application.

8.7.1 Melt Spinning

Melt spinning is most commonly used to produce polymeric fibers because it enables rapid fiber production without the use of solvents. In melt spinning, the molten thermoplastic polymer is extruded through a spinneret (shaped holes), as shown in Fig. 8.4A. Liquid-phase polymer is quenched to the solid-phase upon exiting the spinneret using air, liquid, or a combination of the two. The spinneret design contributes significantly to the size and shape of the final fiber. The fibers are drawn (or stretched) to tune the fiber dimensions, fine structure (e.g., molecular orientation, etc.) and mechanical properties. This well-established fiber production technique presents unique challenges for production of sensing fibers. Most sensing fibers will require integration of two or more materials, including at least one insulator and one conductor. Though techniques exist to simultaneously extrude multiple component materials through the spinnerets, different materials may respond differently to the extrusion, quenching and drawing processes. In melt extruded carbonaceous conducting polymers, for example, drawing speed significantly affects both the viscosity and storage modulus of the extruded material [46]. Bi-component melt extrusion is also affected by shear rates of the flowing polymers as they pass through the spinneret [47]. Conventional spinnerets are designed to extrude fibers with circular cross-sections, and exhibit differences in flow shear rates from the outer edge of the fiber, where they are highest, to the center of the fiber, where they are lowest. When multiple immiscible polymers are extruded, the differences in shear flow contribute to differences in interfacial forces between materials. Even polymeric materials with similar viscosities may

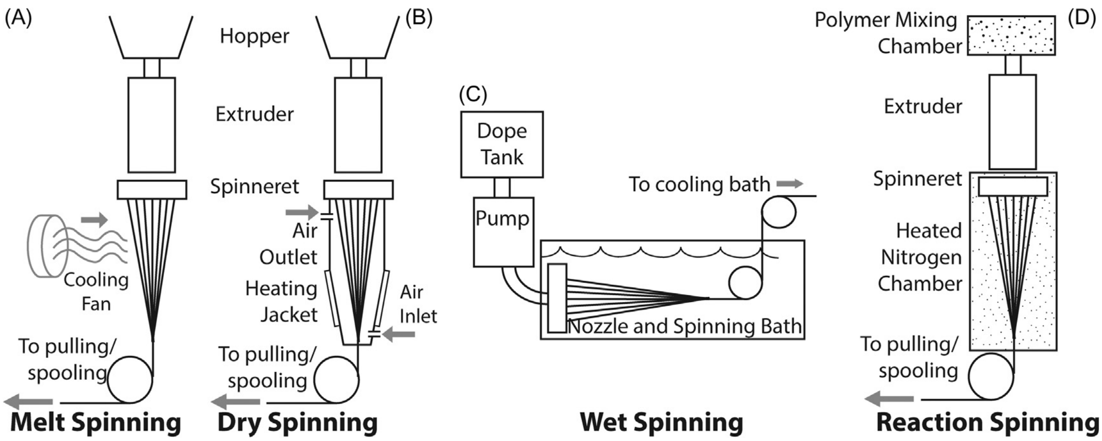

Figure 8.4
Potential methods of multicomponent fiber sensor extrusion. (A) Melt spinning uses cooling fans to solidify extruded fibers. (B) Dry spinning uses heated gases at the extrusion outlet to solidify fibers. (C) Wet spinning uses a submerged spinneret system to cool and solidify fibers. (D) Reaction spinning can be used to induce fiber forming of reactive polymer materials.

suffer from elastic layer rearrangement which causes alterations in the desired cross-sectional geometry. The effects of elastic layer rearrangement are greater for extruded cross-sections of square or teardrop shape than for circular shape, when the colaminar flow path is longer, and when more elastic materials are used [48].

8.7.2 Solution Spinning—Dry spinning/Wet spinning

Solution spinning is generally used to form fibers from polymers that do not form stable melts, but that dissolve in solvents [49]. In dry spinning (Fig. 8.4B), as the polymer solution exits the fiber spinneret, it enters a drying tower where it is exposed to hot gas (generally air) which rapidly removes nearly all of the solvent. The fiber may be further stretched or processed following solvent evaporation. In wet spinning (Fig. 8.4C), the spinneret itself is submerged in a liquid nonsolvent coagulation bath. As the polymer exits the spinneret, the miscible solvent is removed by the liquid bath, causing the skin of the filament to be solidified first. The fiber is stretched while the solvent diffuses out of the polymer making room for the nonsolvent, effecting coagulation. The production of sensing fibers using solution spinning methods presents unique challenges due to the effects of mass transfer that occur as the solvent is removed either in air or in the liquid bath. Because of this mass transfer, the fiber shaping dynamics are more difficult to control, and this process does not lend itself well to producing sensing fibers with unconventional geometries or multicomponent fibers.

8.7.3 Reaction Spinning

Reaction spinning can be used to form polymeric fibers from monomers or prepolymers, as shown in Fig. 8.4D [49]. These components are mixed in solution with additional additives before being extruded through the spinneret. As they exit the spinneret, the filaments are heated and exposed to nitrogen to initiate polymer forming reactions. This method can be used to create polymers with different reactive components providing multiple advantageous properties. Some elastomeric fibers are produced using this method, and this method could potentially be used to produce fibers with unique mechanical properties for strain sensing or biopotential recording.

8.8 Interconnects

An important challenge when making sensors with fiber and yarns is interfacing them with other components using the same ubiquitous materials that they are made from. At the systems level, a sensor that is fully wearable needs to also have wearable interconnects that route the transduced information to a transmission/processing center. On normal printed circuit boards (PCB) this is achieved using metallic pads that sensors can be soldered to. However, when the substrate changes to flexible textiles, new materials and methods are needed to both route and connect conductive textiles to components that have metallic leads.

One of the simplest methods to route circuits in textiles is embroidery. Traditionally, the embroidery process is used for decorating textile fabrics; however, in this application, its main purpose is to route a circuit using conductive fibers or yarns [50]. While this method may seem like the simplest for prototyping, it is difficult to automate due to the limitations of commercially available conductive fibers that can be used for sewing. Another challenge with embroidering is insulating the connections with other materials to avoid electrical shorts when the fabric is deformed. An alternative method to route circuits is through weaving of conductive yarns inside the textile substrate [51]. Weaving allows for conductive fibers to be integrated during fabric production in a roll-to-roll process. More complicated multilayer weave designs can also be used to make vias with the warp and weft fibers traversing from one circuit layer to another. Knitting is a method of fabric production where loops of yarns are interlaced [52]. This method can be used to incorporate conductive yarns in a textile substrate. Knitted fabrics may also be more suitable for printing circuits on textiles when intimate skin contact is needed [53]. A comparison of the advantages and disadvantages of these routing methods can be found in Table 8.1A.

Once these circuits are routed in a textile substrate, they will need to be connected to common integrated circuits with metallic leads. While some metallic yarns can withstand soldering temperatures, this kind of a connection is not flexible and is easy to break if mechanical movement is present. Mechanical gripping is a simple way to connect a fiber to a metallic lead [50,54]. Sewing the conductive fiber through a metallic connection or crimping it in a metallic connector are two examples of the mechanical gripping technique. Although this connection is simple to implement, its susceptibility to damage due to mechanical movement and humidity make it unreliable to use on textile substrates. Another way of connecting a conductive fiber to a metallic lead is by applying a conductive epoxy which secures the connection physically and reduces the effect that movement and humidity have on the electrical connection quality [55]. Conductive epoxies are made with conductive particles that provide electrical connection. A semi-flexible connection can be achieved if the conductive epoxy material is made with a flexible polymeric material. Table 8.1B offers a comparison of the commonly used textile-to-circuit interconnect methods. A need still exists for research and development of more reliable, highly conductive interconnects for interfacing sensing textile fibers with corresponding circuitry.

8.9 Challenges of Fiber-Based Sensing

Though fiber-based sensors show promise for enabling next-generation electronic textiles, there are still major hurdles to overcome for these sensors to be realized in commercial

Table 8.1: (A) Textile Routing Methods. (B) Textile-to-Circuit Interconnect Methods.

	Advantages	Disadvantages
A		
Embroidery	– Simple to prototype by hand – Can be performed on a final product – Independent of fabric formation processes – Routing can be done along the shortest path	– Difficult to automate – Needs to be sealed to prevent electrical shorting
Woven conductive yarns	– Roll-to-roll, highly automated process – Wider choice of conducting yarns – Stable and robust structure – Vias possible	– Crossover point interconnect required – May not be suitable for next-to-skin products – Needs to be sealed to prevent electrical shorting
Screen printing	– Can be performed on a final product – Independent of fabric formation processes – Stretchable and flexible – Routing can be done along the shortest path	– Relatively fragile
Knitting	– Roll to roll, highly automated process – Fully fashioned and whole garment knitting possible – More suitable for next-to-skin garments	– Limited choice of conducting yarns
B		
Soldering	– Common and easy process – Strong mechanical and electrical connection	– Connection not flexible – Requires the use of a temperature resistant metallic fiber/yarn
Mechanical gripping	– Connection is based on tension (i.e., gluing material not required)	– Humidity and mechanical movement affect the electrical connection quality – Brittle connection
Conductive epoxy	– Flexible connection if flexible epoxies are used – Robust electrical connection	

applications. The need for fiber-based sensors that produce a stable, repeatable sensor response demands precise fabrication methods and highly efficient interconnect methods. All materials must be able to withstand repeated mechanical cycling, as well as washing and drying without degradation in sensor response and stability. For improved fiber-based sensors, novel materials are needed for insulating segments, conducting segments, and sensing elements. In order to be used for healthcare applications, fiber-based sensors must be benchmarked against highly accurate and precise healthcare sensors that are currently used in clinical settings. Fiber-based sensors are more likely to find use in applications of remote health/wellness monitoring, where sensors may not provide specific diagnoses but can indicate the need for further health evaluations.

8.10 Conclusion

As a natural interface between humans and their environment, textiles offer tremendous surface area to functionalize and deploy sensors, actuators, and other devices ubiquitously and with relatively lower production costs. In this chapter, we discussed the need in e-textile-based sensors for the ability to (i) integrate various electronic functionalities into textiles in a truly unobtrusive manner, and (ii) preserve the unique and essential "textile" characteristics of fibrous structures, such as strength, flexibility, texture, softness, porosity, comfort, and stability. We presented a systematic report on sensory characteristics of a strategically designed textile structure, assembled from coextruded multicomponent fibers that are capable of generating useful electrical response under various stimuli. These fabrics utilize the unique structural and material characteristics of coextruded multicomponent fibers to create sensing element crossover points for concurrent detection of multiple physical parameters.

8.11 Conflicts of Interest

The authors acknowledge that they had no involvement in the development of fiber sensors or related sensing systems for commercial gain at the time of writing of this book chapter. The authors are engaged in publicly funded research on the topic of fiber-based sensors and were involved in the publication of certain references used throughout the chapter.

Acknowledgments

The authors would like to acknowledge the support of the North Carolina State University Chancellor's Innovation Fund, as well as the National Science Foundation (NSF) for grants ECCS-1509043, IIS-1622451, and DGE-1252376 (NSF Graduate Research Fellowship). We would also like to thank Kony Chatterjee, Ashish Kapoor, Hannah Kausche, and Jordan Tabor for providing insight during the preparation of this book chapter.

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