Electronic textiles and their potential

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Textile materials are generally lightweight, flexible and unique in many ways compared to other materials. Most importantly, they are omnipresent in our lives. Textiles are necessary next to our skin as well as in our environment. They are used for comfort and protection as well as fashion. In the near future, almost all textile products including what we wear and walk on seem destined to be transformed from their present to multifunctional, adaptive and responsive systems. The functions may include communication, computation and entertainment, as well as health care and threat detection. Textiles used in non-apparel applications may perform surveillance and detection functions. Some of the concepts being explored currently may revolutionize our understanding and appreciation of fiber-textile products. This paper reports the developments in the field of electronic textiles, focusing on the current state-of-the-art of electrotextile products and the research being carried out in this field.

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1 Introduction
Electronic textiles or electrotextiles can be described as textile products with 'integrated' electronic capabilities. The level of the integration at this point may vary from simply using a textile product as a platform with plugged in passive electronic devices to higher level integration of electronic capabilities designed or fabricated into a fiber or textile substrate. The ubiquitous textile products having large surface area and other desirable characteristics (lightweight, etc.) are obvious choices as platforms for deploying sensors and other electronic devices over large areas in an economical manner. It has been an active area of research in recent times and by all indications seems to be gathering steam. Many commercial electrotexile products are already being manufactured and marketed. In the last Techtextil trade fair in Frankfurt, Germany, there were about ten companies displaying their products ranging from fabric-based heating systems to keyboards.

Currently, electronic textiles are being developed for many applications, including biomedical sensing, wearable computing, and large area sensors. Ongoing research and development activities in this area are truly multidisciplinary; it is envisioned that the fundamental research being carried out in areas of materials/polymer science and various engineering disciplines are likely to result in future unobtrusive electronic devices, sensors, batteries and solar cells, fully integrated at the fiber/polymer level or built into the textile structures. The possibilities that this technology holds seem almost limitless.

In a world which is becoming rapidly interconnected by technology, the assimilation of these technologies to other systems in use today, as well as specifically targeted designs for future products, will not only lead to enhanced functionalities in existing products but also will spawn new products. This paper reports the recent developments in electronic textiles and highlights the ongoing research and development in this fast-growing field.

2 Electronic Textiles Today
Examination of the current state-of-the-art of electrotexile products being manufactured as well as being developed generally reveals two clearly delineated areas of this technology in terms of the level of integration of electronics in textile materials. Textile product and/or fabric level integration of electronics seem to be more common today. This includes many examples of textile products that are used primarily as a carrier to plug in electronic devices, in some instances, into data buses integrated into the fabric. Examples of fiber/polymer level integration at this point are few. Most of these concepts are currently the subjects of research. The discussion that follows includes the applications in

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what has been termed more recently as electrotextiles as well as some of the traditional uses of conductive fibers or other materials in textiles.

2.1 Electromagnetic Induction (EMI) Shielding

Conducting fibers have been used for a long time in producing fabrics used for electromagnetic shielding and for electrostatic charge dissipation. Fabrics containing conducting fibers or coated with conducting polymers, like polyaniline and polypyrrole, provide effective shielding from radiated electromagnetic interference. Kim et al. have developed polypyrrole coated polyester fabrics with relatively low surface resistivities for providing shielding against electromagnetic interference. Kuhn et al. have discussed the EMI shielding properties of polypyrrole coated polyester fabrics. A patent by Ebner and Fitzky describes a layered arrangement of metallized textile sheets (separated by insulating layers), which is used for screening electromagnetic waves in the broad range from 10 MHz to 1000 GHz. These textile-based metallized sheets are flexible and conformable, have elastic properties, and attenuate the electromagnetic radiation in transmission by 30 - 40 dB. Another patent by Dordevic describes the development of a fabric with transparent conductive coatings on a woven base, which can be used in contact with metal substrates. Kuhn and Kimbrell describe conductive textiles in which conductive polymer films are patterned on certain selected areas of woven or knitted fabrics according to given designs or patterns. Post et al. have described the use of electronic embroidery as a means of patterning conductive textiles by numerically controlled sewing processes to produce electronic textile products. They have described applications of textile-based circuitry in fabricating fabric keyboards, pressure sensors, and others. One of the most significant recent developments in the application of conducting threads to electronics has been the attempt to form networks of conducting threads in a fabric by weaving or knitting. Electrically or optically conducting fibers are arranged and woven in a particular manner so as to transmit electrical or optical signals from one part of the fabric to the other for communication between different devices placed on a fabric or for wireless coupling with a remote electronic device. In a patent by Lebby et al., a communicative wristwatch which consists of a wristband made up of woven conductive yarns, an electronic unit and a power source integrated into the woven wristband, has been described. The wristband has conductive and non-conducting fibers woven orthogonal to one another to define a simple grid. The conductive fibers/yarns provide wired coupling between the electronic unit and the power source, and with all other components attached to the wristband. The woven conductive fabric can also act as an antenna for transmission and receipt of signals.

2.3 Thermal Applications

Conductive fibers are being used for many thermal applications like flexible heating pads, electrical heating blankets and jackets. Blankets and jackets that use stainless steel microfibers and yarns woven into a fabric have been developed by Polartec. Based on the principle of resistive heating of the conductive elements, these conductive yarns act as a heating source and provide uniform distribution of heat throughout the entire fabric. A heating jacket was also developed by North Face with electrical wires integrated into the jacket.

2.4 Circuits and Circuit Boards

Electrical circuit built into a textile substrate is one of the necessary building blocks of electronic textile products. Flexible circuit boards on fabric substrates using printing techniques have been reported. Patents by DeAngelis et al., Pittman and Kuhn, Gregory et al., and Kuhn and Kimbrell describe conductive textiles in which conductive polymer films are patterned on certain selected areas of woven or knitted fabrics according to given designs or patterns. Post et al. have described the use of electronic embroidery as a means of patterning conductive textiles by numerically controlled sewing processes to produce electronic textile products. They have described applications of textile-based circuitry in fabricating fabric keyboards, pressure sensors, and others. One of the most significant recent developments in the application of conducting threads to electronics has been the attempt to form networks of conducting threads in a fabric by weaving or knitting. Electrically or optically conducting fibers are arranged and woven in a particular manner so as to transmit electrical or optical signals from one part of the fabric to the other for communication between different devices placed on a fabric or for wireless coupling with a remote electronic device. In a patent by Lebby et al., a communicative wristwatch which consists of a wristband made up of woven conductive yarns, an electronic unit and a power source integrated into the woven wristband, has been described. The wristband has conductive and non-conducting fibers woven orthogonal to one another to define a simple grid. The conductive fibers/yarns provide wired coupling between the electronic unit and the power source, and with all other components attached to the wristband. The woven conductive fabric can also act as an antenna for transmission and receipt of signals.
Recently, Dhawan et al.\textsuperscript{22-24} reported fabrication of electrical circuits in woven fabrics. They explored various potential methods to form interconnects and disconnects at crossover points in woven circuits, necessary to route signals. They found resistance welding as an effective means of forming the interconnects. They also discussed two kinds of resistance welding processes, i.e. top-bottom probe welding and parallel gap welding. Interestingly, they reported formation of disconnects—necessary to route signals using parallel gap resistance welding.\textsuperscript{22} Scanning electron microscope (SEM) images of resistance-welded and unwelded fabric samples of copper and steel conductive threads reported by Dhawan et al.\textsuperscript{22-24} is shown in Fig. 1.

In designing fabric-based circuits, signal integrity issues (crosstalk noise) are also of importance. Dhawan et al.\textsuperscript{24} observed that the magnitude of crosstalk noise increased as the spacing between the conducting lines decreased (Fig. 2). They reported significant reduction in crosstalk noise when twisted-pair and coaxial yarns were used to form these circuits.

2.5 Sensing Devices and Systems

The area of sensing may be the most active research area in electrotexiles. Unobtrusive sensing of human physiological signs to sensing of external environmental parameters including threat are major areas of interest. Woven fabric networks with integrated sensing elements have already been described. Inaba et al.\textsuperscript{25} described a conducting fabric-based tactile sensor system in which a garment made from a multilayer sensing fabric covers the entire body of a robot. This fabric helps the robot to sense whenever any object or human being touches it. Fully integrated fabric-based tactile sensors in this sensor suit are distributed on the entire body of the robot and a network of conducting fibers conveys the sensed signals to the sensor processor. De Rossi et al.\textsuperscript{26-28} at the University of Pisa have done some of the pioneering work in the area of strain sensing using textile substrates. Their work is relevant for many applications, including motion sensing and physiological monitoring. De Rossi et al.\textsuperscript{26} demonstrated remarkable strain and temperature sensing capability of conventional elastomeric fabrics coated with a thin layer of conducting polymer polypyrrole. They demonstrated the piezoresistive properties of these fabrics by fabricating a sensing glove. The change in resistance caused by fabric strain due to finger movement was measured. Lorussi et al.\textsuperscript{28} applied the same concept to instrument a sleeve that is capable of sensing body posture. They used printed carbon filled rubber layers on fabric and created an interconnected array of sensors to determine the surface strain fields induced by movement. The composite material used in the sensor fabrication has appropriate level of conductive particles embedded in an elastomeric binder. Resistivity of the of the composite is altered due to application of pressure.

![Fig. 1—SEM micrographs of copper (light) and polyester (dark) threads. Plan view of a welded interconnect using (a) top-bottom probe resistive welding, and (b) parallel-gap resistive welding.](image)

![Fig. 2—Crosstalk noise between woven interconnect lines for a 1volt signal (1 MHz frequency) sent into an aggressor line: (a) signal on the quiet line for 0.125 inch spacing between parallel twisted pair lines, and (b) crosstalk noise vs. spacing between twisted pair and bare copper lines.](image)
Various sensing devices and systems compatible with textiles (or sometimes textile based) for continuous monitoring of physiological and behavioral parameters for health care have been proposed. In all cases, the use of functionalized materials enabled design and fabrication of sensors and electrodes. Scilingo et al. reported the use of knitted fabrics made of stainless steel wrapped viscose yarn as electrodes to monitor signals of electrocardiogram and electromyogram. Additionally, they also reported the use of elastic fabrics coated with carbon loaded rubber to monitor respiratory changes. Similar efforts to design electrodes and strain sensors for health monitoring have also been reported by Paradiso et al.

The development of garments with capabilities to continuously monitor the wearer’s biomedical information and body vital signs, environmental conditions, and garment penetration by a ballistic material have also been reported. In a patent by Jayaraman et al., a complete process for the development of a woven garment with intelligence and sensing capabilities has been described. One of the intelligence capabilities of the garment (called Sensate liner) described in the patent is the ability to monitor garment penetration by a ballistic material and this intelligence capability can be achieved by including optical fiber sensing components in the weave of the garment. Another such sensor system developed is the life-shirt system which is used to collect physiological data of patients without affecting their normal routines. Sensors and conductive elements are woven into the life-shirt at optimal locations (near the chest and abdomen) to get data on the patient’s respiratory system.

Jones and Leftly at SOFTSwitch Ltd have developed a technology that enables fabric-based materials to be used for pressure sensing. The mechanism of sensing is similar to what has been described earlier. Soft switch fabrics show a very broad resistance change when compressed. The soft switches can be used for occupancy sensing based on seat pressure mapping for fabric control surfaces in automobiles, airlines, home furnishings and floors, for wearable computing, and for developing keypads (Fig. 3). In a patent by Gilbert and Boyce, a fabric-based weight sensor for the seat of a motor vehicle has been described. This sensor includes a compressible, preferably foam layer disposed between two conductive fabric layers. In another patent by Sandbach et al., a laminate conducting fabric sensor has been described. It consists of two conducting planes (with strips of conductive lines) separated by a mesh of insulating fibers. On application of pressure, the outer conducting planes are brought into mechanical contact through the insulating mesh. The amount of current flowing as a result of this contact will vary in dependence upon the actual position of the plane where the mechanical interaction takes place.

Application of context awareness to wearable electronics has been discussed in several papers. Context awareness can be defined as making the electronic devices carried by people in everyday life more aware of the environment and activity of the users so that the functionality of the devices could be modified accordingly to suit the activities and situation of their wearers. This context awareness can be achieved by using sensors that can feed information into the electronic devices carried by the user. In a paper by Randell and Muller, a method of determination of context awareness using Global Positioning Systems (GPS) has been described.

El-Sherif et al. have integrated optical fiber-based chemical and biological sensors into uniforms of soldiers. A miniature chemical sensor has been developed for the detection of the presence of organophosphate dimethylmethylphosphonate (DMMP) gas. Development of the sensor includes replacing the cladding material of the optical fibers with active
materials like polypyrrole and polyaniline. Exposure to DMMP changes the refractive index of fiber cladding material (polypyrrole) and thereby reduces the transmitted intensity of light signal transmitted through the optical fiber. These optical fiber sensors have been integrated into woven (with twill, satin and plain weaves) and knitted structures. Influence of the different fabric structures and constructions on the loss of intensity of signals transmitted through the woven or knitted optical fibers has been studied. El-Sherif et al. have also reported the incorporation of fiber optic strain sensors into textile structures.

2.6 Energy Storage and Harvesting Devices

Power supply is an essential component of electronic textile products. A number of publications reported developments in this area. Reppelinger and Coates disclosed development of a nonwoven fabric battery electrode in a patent. It uses conductive fibers to form a porous mat, which is used as a negative electrode for a hydrogen storage cell. In another patent by Ikkanzaka et al., the development of nonwoven fabrics for a storage battery separator has been described. This sheet has a property of holding electrolytes and is produced from conjugate fibers that have a specific cross-sectional form. These conjugate or bi-component fibers are formed using the melt extrusion process with one of the components of the fiber being a random copolymer of ethylene and polyacrylic acid and the other being polypropylene. These developments have paved the way for the development of batteries based entirely on textiles. Innis et al. have reported the development of complete textile-based batteries. Inherently conducting polymers are also being developed for wearable energy storage systems. These fabric batteries and photovoltaics have been developed utilizing ionic liquid electrolytes that could be incorporated into textile membranes. Fabric-based electrodes have been used to form a flexible and conformable battery system. These textile-based electrodes were formed by coating conducting polymeric materials on fabrics or by in situ or vapor phase polymerization of the monomers of conductive polymers on fabric substrates.

Significant research is being carried out in the development of flexible and conformable solar cells. Samuelson et al. have reported development of solar cells on polymeric films and woven fabrics by coating these substrates with organic dye molecules and titanium dioxide. The mixture of organic dye molecules and the titanium dioxide nano-particles is sandwiched between two conductive electrodes. There is a layer of electrolyte present between the organic dye and titanium dioxide mixture and the lower electrode. The top conductive electrode is transparent and allows light to pass through it and react with the organic dye molecules. There is charge generation due to the absorption of light by the dye molecules. The charge generated is transferred to the titanium dioxide nano-particles and collected by the electrodes, thereby producing electrical energy from solar energy.

2.7 Transistors on Thin Films/Threads

In the area of flexible electronics and electronic textiles, one of the most significant research developments is the fabrication of transistors on thin films that could be slit into narrow films and woven into a fabric (Fig. 4). Research in this area is being carried out at Princeton, North Carolina State, and North Texas Universities. Fabrication of these transistors has been done on amorphous silicon. Layers of n-doped and intrinsic amorphous silicon are deposited on silicon nitride, which is deposited at a low temperature on flexible Kapton films and the transistors are formed on the amorphous silicon. Plasma enhanced chemical vapor deposition process was used for the deposition of amorphous silicon and silicon nitride. The gate, source and the drain contacts of the transistor are deposited by using thermal
deposition. All the patterning is done using conventional photolithography. The films with transistors formed on it are cut into thin strips which are then woven into a fabric-like structure. Interconnections between the different transistors are made using conductive strips to demonstrate digital logic functionality. Development of these transistors is significant because it proves that if good quality transistors could be fabricated on thin films and these thin films could be woven into a fabric, an all fabric-based integrated circuit could be formed on fabric substrates at the speed of large-scale fabric production. Lee and Subramanian reported fabrication of transistors directly on fibers without using conventional lithography process. They achieved patterning via shadowing from fiber to fiber crossover.

3 Future of Electronic Textiles

Based on the current state of electronic textiles research, it can be assumed that in the short term, the field of electronic textiles would involve attachment of electronic devices, sensors, etc. to conductive elements integrated into a textile to form flexible electronic products. In the long run, inconspicuous devices, including power supply and some level of information processing will be built into the structures of the fibers, yarns and fabrics. Many other issues such as redundancy, fault tolerance, packaging, etc. have to be addressed. Additionally, all-polymer or polymer-metal conductive ‘textile’ yarns have to be developed to replace currently used connecting medium copper or steel. The future of electronic textile products not only include wearables to address individual needs but also sensor arrays useful for civilian and military applications. Additionally, in the future, the electroactive materials are likely to be incorporated into textile structures to make it adaptive and responsive to allow for shape, surface and structure modification desirable for many applications. It is envisioned that future electronic textiles would have both sensing and actuation elements built into it.

References


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