Piezoelectric energy harvesting from intelligent textiles

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9.1 Introduction

Intelligent textiles are textiles that are able to detect changes in their surroundings and react to them (Zhang and Tao, 2001). They are textiles that react to some external stimulus from their surroundings and produce a practical outcome. The induced stimulus and the consequent response could be chemical, electric, thermal or some other type in nature (Van Langenhove and Hertleer, 2004). Intelligent textiles can also be called smart textiles.

This chapter discusses in depth various types of energy harvesting textiles, their testing methods and applications as viable energy sources. It also introduces the use of piezo-, pyro-, ferro- and dielectric materials in intelligent textiles. Various piezo materials, their structures and dipole formation characteristics are explained. Method of manufacturing various piezo fabrics as woven, knitted and composite structures is presented. Testing of piezo fabrics is included in this chapter. Finally, the application areas for energy harvesting in intelligent textiles are explored.

9.2 Piezoelectric materials

The piezoelectric phenomenon could be described as one of the substantial discoveries of the 19th century. The term piezo is derived from the Greek word *piezein*, meaning pressure (Kholkin et al., 2008). Piezoelectricity is electricity produced due to pressure exerted on a piezoelectric material.

Piezoelectric, pyroelectric and ferroelectric materials are often discussed simultaneously, owing to their interrelationship with each other at the crystalline structure level. For a crystalline structure to exhibit piezoelectricity, there should be no symmetry at the inversion centre for point group(s) (Tilley, 2006). A piezoelectric material can show both pyroelectricity (generation of electric charge on a crystal by change of temperature) and ferroelectricity (a property of certain materials that have a spontaneous electric polarisation). The relationship between different types of materials is shown in Figure 9.1. Ferroelectric materials are known to have superior piezoelectric properties over their non-ferroelectric counterparts.

There are different piezoelectric materials based on the various crystalline properties. These materials can also be classed according to their source, such as natural or

Electronic Textiles. http://dx.doi.org/10.1016/B978-0-08-100201-8.00010-2

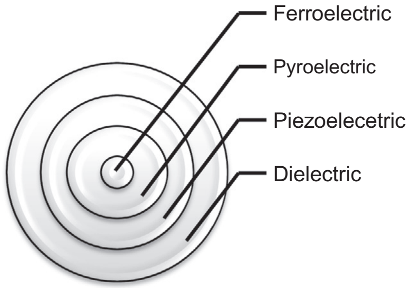

Figure 9.1 Relationship between ferroelectric, dielectric, piezoelectric and pyroelectric materials.
Adapted from Kong et al. (2014).

synthetic. Natural materials such as quartz, bones, tendons, enamel, dentin and others are known to exhibit piezoelectric properties. Generally, the crystalline structures can be classed according to seven basic crystal systems: triclinic, monoclinic, orthorhombic, tetragonal, rhombohedral (trigonal), hexagonal and cubic. These form 32 various types of point groups, of which 21 are non-centrosymmetric. Of these, 20 are piezoelectric. Out of these, 10 are pyroelectric crystals, which become permanently polarised in a certain temperature range (Kong et al., 2014). Pyroelectric crystals are different from thermoelectric crystals in terms of the fact that the whole crystal (not just a portion of the device) undergoes a temperature change, causing a temporary voltage. Amongst these 10 pyroelectrics are ferroelectric crystals such as $BaTiO_3$, $PbTiO_3$, which are characterised by the formation of electrical dipoles due to asymmetrical shifts in the equilibrium positions of ions.

9.3 History of piezoelectricity

In a review regarding piezoelectricity, Ballato (1996) revealed that Coulomb was the first to suspect that electricity generation could be attained through applying pressure to materials. Katzir (2006) pointed out that Jacques Curie and Pierre Curie were the first to observe piezoelectricity in 1880. It is interesting to note that in 1881, it was not the Curie brothers but Lippmann (1881) who announced the existence of a converse piezoelectric effect. Basically, this converse effect is deformation of a piezoelectric material due to influence of an applied electrical field. Lippmann (1881) postulated the existence of this effect through mathematical prediction by applying basic thermodynamic principles to reversible processes. Curie and Curie (1881) verified and established the converse piezoelectric effect experimentally soon after.

In early years after this discovery, theories governing the effect were formed and modified. It was not until the first World War that the earliest applications of the piezoelectric effect were developed in the form of sonar devices to detect submerged metal objects in water (Katzir, 2006). As indicated by Sharapov (2011), shortly after the first sonar device was built, other devices such as piezoelectric microphones, sound recording and receiving equipment, together with measuring instruments for force, acceleration and vibration were created based on the piezoelectric principles. Since then, a lot of studies have been made on the uses of piezoelectric materials, particularly for energy generation.

A more recent and novel approach is energy generation using nanostructured piezoelectric devices called nanogenerators, which transform kinetic energy into electrical energy using different types of materials such as ZnO, ZnS, GaN, CdS, PVDF (polyvinylidene fluoride) and $BaTiO_3$ (Chang et al., 2012).

9.4 Basic principles

9.4.1 Charge formation and poling

The piezoelectric materials are a part of the ferroelectric family, in which the molecular structure orientation causes the formation of electrical dipoles due to localised charge separation, as shown in Figure 9.2. A group of dipoles with parallel orientation are called Weiss domains. These Weiss domains tend to be randomly oriented in a raw piezoelectric material (Figure 9.2a), hence the material does not show any piezoelectric response. However, when the material is heated above its Curie temperature (T_c) in the presence of a strong electric field, these dipoles reorient themselves in the direction of the applied field, as seen in Figure 9.2. On cooling, the material tends to maintain the dipolar orientation achieved during heating, as seen in Figure 9.2.

Table 9.1 shows a comparison between various piezoelectric materials and their properties. The piezoelectric coefficients in ceramics are higher than those in polymers. Hence, on application of pressure, the electrical output tends to be higher for piezoceramic materials. The electromechanical coupling constant (k_{31}) for ceramics such as PZT ($(Pb[Zr_xTi_{1-x}]O_3$, $0 \le x \le 1$) is 2.5 times higher than for PVDF ($-(C_2H_2F_2)_n-$), showing the enhanced ability of ceramics to convert stress to electrical output. However, the piezoelectric voltage coefficient in PVDF is higher than in ceramics (21 times that of PZT).

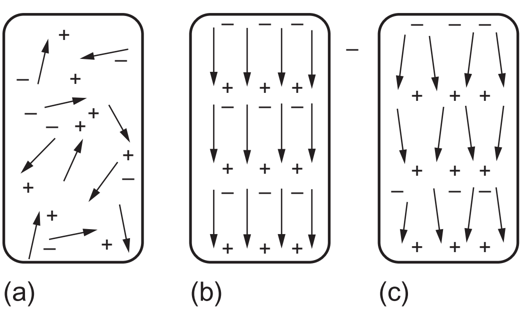

Figure 9.2 Dipole reorientation on application of an electric field (Shah, 2011).

Table 9.1 Properties of various commercially available piezoelectric materials

Property	Units	$BaTiO_3$	PZT	PVDF
Density	10^3 kg m^{-3}	5.7	7.5	1.78
Acoustic impedance	10^6 kg m^{-2} s	30	30	2.7
Relative permittivity	$\varepsilon/\varepsilon_0$	1700	1200	12
Piezoelectric strain coefficient (d_{31})	10^{-12} C N^{-1}	78	110	23
Piezoelectric voltage coefficient (g_{31})	10^{-3} V (m N^{-1})	5	10	216
Pyroelectric voltage coefficient (Pv)	(V μm^{-1}) K	0.05	0.03	0.47
Electromechanical coupling constant (k_{31})	%@1 kHz	21	30	12

Adapted from Vatansever et al. (2012a).

9.4.2 Direct and converse effects

The idea of putting pressure on a material to produce an electrical output can be referred to as a 'direct' piezoelectric effect. The electrical output generated in the direct effect is due to the applied mechanical stress on the material, which produces an electric charge on the surface of the crystals. The polarity of the charge produced can be inverted by changing the direction of the strain. This effect can also be reversed, producing a 'converse' piezoelectric effect. The application of an electric field across the crystal results in a mechanical deformation, realised as a change in its dimensions (Haertling, 1999; Kong et al., 2001, 2008; Vatansever et al., 2012b; Damjanovic, 1998). Figure 9.3 shows the effect of applying tension and compression to a piezoelectric material (direct effect).

9.5 General theory of mechanical energy conversion

Piezoelectric materials work on the basic phenomenon of conversion of structural vibrations into electrical outputs. Piezoelectric materials tend to produce electricity when pressure is applied. This pressure causes a change in the polarity of the dipoles, which results in an imbalance between the two surfaces where the two ends become polarised. The types of deformations causing this imbalance can be bending, mechanical compressive stress, mechanical strain, tensile stress and strain. Piezoelectric generators are able to produce relatively high voltage outputs but low electrical currents. Output impedance also tends to be high with piezoelectric materials (>100 kΩ) (Beeby and White, 2010). Lee et al. (2012) have demonstrated that the M13 of certain bacteriophages can be utilised for piezoelectric energy harvesting.

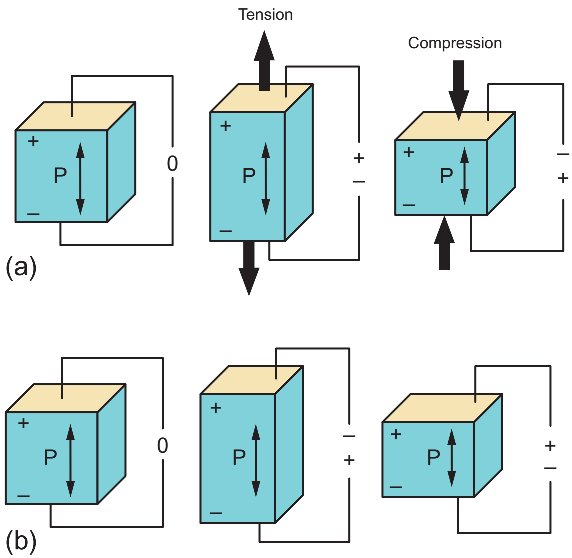

Figure 9.3 Direct (a) and converse (b) piezoelectric effects. Adapted from Vatansever et al. (2012b).

Piezoelectric coupling factors (e.g. k_{33}, k_{31} and k_p) refer to the overall strength of electromechanical effects. These are the square root of the ratio of electrical energy output to the mechanical energy input. The value of k is always less than unity due to the inability of complete conversion of electrical to mechanical energy, and vice versa. The coupling factor k_{xy} measures the effectiveness of a piezoelectric material and can vary in different directions within a material. The piezoelectric charge coefficient, also known as the piezoelectric modulus with the symbol d, describes the change in volume on application of an electric field. Values of d have magnitudes of the order of 10^{12} C N^{-1} (direct effect). This can become 10^{-12} m V^{-1} in the case of the converse effect. There can be many piezoelectric coefficients (i.e. d_{xy}), where x relates to the direction of generation of polarisation in electrodes perpendicular to the vertical direction, and y refers to the applied mechanical stress in the lateral direction. For example, d_{31} means that this piezoelectric coefficient relates to the generation of polarisation (direct effect) in the electrodes perpendicular to the vertical direction (3) with the stress being mechanically applied in the lateral direction (1), while d_{33} indicates the polarisation generated in the vertical direction (3) when the stress is applied in the same direction. Hence, d is an important indicator for piezoelectric materials.

The piezoelectric voltage constant, also known as the g factor, denotes the electric field generated by materials per unit of mechanical stress applied. Like the piezoelectric charge constant, these values can also be classed in terms of directions (i.e. g_{xy}).

Permittivity, the dielectric constant, ε, quantifies the dielectric displacement obtained per unit electric field applied. ε^T and ε^S denote the permittivity at constant stress and strain, respectively, with terms such as ε^T_{11}, ε^S_{11}, ε^T_{33}, ε^S_{33}.

Elastic compliance, s, is the reciprocal of Young's modulus, or the strain produced as a result of applied mechanical stress. s^D and s^E are two types of elastic compliances, which denote compliance under constant electric displacement and electric field, respectively. The direction of applied stress or strain is represented by s_{xy}, where x is the direction of strain, and y is the direction of stress.

Young's modulus is the measure of the elasticity or stiffness of a material and is denoted by Y. It is a ratio of stress applied to strain produced.

9.6 Different piezoelectric materials

9.6.1 Piezoceramics

Piezoceramics, a significant group of piezoelectric materials, are ferroelectric materials with polycrystalline structures (peroskite, tetragonal/rhombohedral crystals). Above the Curie temperature, these crystals exhibit simple cubic symmetry in structure. There are no dipoles present in this state, as the positive and negative charge sites are coincident due to the centrosymmetric structure. However, this symmetry is no longer present below the Curie temperature, where the charge sites are no more coinciding. This results in built-in electric dipoles, which are reversible. Neighbouring dipoles realign locally to form Weiss domains.

Lead zirconate titanate (PZT), barium titanate ($BaTiO_3$), lead titanate ($PbTiO_3$), potassium niobate ($KNbO_3$), lithium niobate ($LiNbO_3$), lithium titanate ($LiTaO_3$), sodium tungstate (Na_2WO_3) and zinc oxide (ZnO) are some of the most typical piezoceramics. Of these, PZT is the most widely used due to its superior performance. However, the toxicity of lead has raised concerns over the use of PZT. A restriction on the amount of lead present has been placed and is focused at eliminating its use eventually. Nevertheless, PZT has no rival at present.

9.6.2 Piezopolymers

Piezopolymers are a fascinating piezoelectric group of materials, having good piezo performance and much higher flexibility than piezoceramics. Natural polymers such as polysaccharides, proteins and polynucleotides have shown some piezoelectric properties (Fukada, 2000). The polymers have superior benefits over other materials due to their ability to form yarns and fabrics. Polyvinylidene fluoride (PVDF) is a piezoelectric polymer with remarkable piezo properties and is a highly suitable material for textile applications.

9.6.3 Piezocomposites

Some materials may have excellent piezo properties, but are not suitable for certain applications due to their characteristics. Piezoceramics are a classic example of such materials where the brittleness of these limits their advantages. In such cases, a piezocomposite can be formed consisting of piezoceramics. These may be arranged in several shapes and geometries such as rod, diced, honeycomb and shell structures (Tressler et al., 1999). Also, the piezoelectric properties of certain materials can be enhanced with additional substances.

9.6.3.1 Nanowires

Nanowires can be described as minute structures having diameters in orders of less than or equal to nanometres (1 nm = 10^{-9} m) and can be of unspecified length. In piezoelectric materials, these nanowires are shown to enhance the piezoelectric effect. Li et al. (2013) have used Ag nanowire-doped PVDF and found that the beta phase contents were enriched by the use of these nanowires. Zeng et al. (2013) have used $NaNbO_3$ nanowires mixed in PVDF in electro-spun non-woven webs. Yang et al. (2012a) have demonstrated the use of ZnO nanowires, which yielded a peak open-circuit voltage of 58 V and a corresponding maximum power density of 0.78 W cm^{-1}. Some other materials such as InN, GaN, CdS and $KNbO_3$ can also be used in a similar manner (Huang et al., 2010; Lin et al., 2008, 2011; Yang et al., 2012b).

9.6.3.2 Carbon nanotubes

Carbon nanotubes (CNT) are nanostructured materials with superior mechanical, thermal and electrical properties. They can be classed as single-walled nanotubes (SWNT) or multi-walled nanotubes (MWNT). The SWNT can be thought of as a one-atom-thick layer of graphite, whereas MWNT as multiple concentric rolled layers of carbon atoms. They are highly useful in contributing to the properties of nanoscale structures. Levi et al. (2004) have investigated the properties of a PVDF-CNT matrix. They used both SWNT and MWNT and claimed that the piezoelectric and pyroelectric behaviours were enhanced remarkably over their parent polymer.

9.6.3.3 Copolymers

PVDF copolymers have been investigated for their piezo properties and for uses in various applications such as sensors. An example of a PVDF copolymer is polyvinylidenefluoride-co-trifluoroethylene [P(VDF-TrFE)], which is a ferroelectric, crystalline polar polymer that exhibits inherent piezoelectric and pyroelectric responses with low acoustic impedance. Such properties provide an optimistic approach towards the use of these polymers for various applications in the near future. Higashihata et al. (1981) compared the piezoelectric constants of PVDF and P(VDF-TrFE) and observed that much larger values were obtained for P(VDF-TrFE) under the same polarizing conditions. The special interest in this copolymer is also due to the evidence reported by Furukawa et al. (1981) that the PVDF-TrFe copolymer can be annealed to 100% crystallinity, as opposed to 50% in PVDF. Other copolymers have also been explored to determine an enhanced piezo effect (Poulsen and Ducharme, 2010).

9.7 Manufacturing piezo textiles

There are many piezoelectric devices, such as sensors, actuators, frequency controllers, transducers and others (Uchino, 2010). Piezo textiles could be developed using various types of piezo fibres along the lines described below.

9.7.1 Piezo fibres

Depending on the type of manufacturing technique used for constructing piezo fabrics, either piezo fibres or yarns would be required. A piezo fibre could be either a short or continuous filament fibre having a high length-to-thickness ratio. The best suitable resources to produce such fibres would be flexible materials such as polymers, which have the tendency to bend and form into fibres. Fibres could also be produced directly from piezo materials such as piezoceramics. In addition to energy harvesting, the piezoceramic fibres could have other benefits as well, such as better piezoelectric activity and higher working temperatures. However, for obvious reasons, ceramic fibres are less feasible for use in garment applications. Another broad area is the development of composite piezoelectric fibres. Pinet (2008) suggested that such high-aspect-ratio fibres could be used for *in vivo* endovascular imaging and acoustic microscopy inside acoustically opaque organs.

9.7.1.1 Wrapping/twisting

Wrapping is a yarn formation technique whereby parallel fibres as a thick inner core are wrapped by the wrapping material. This process imparts extra strength especially to staple filaments. The resulting yarn is a high-strength structure with properties combining both the core and wrapping material. The core may be fully or partially enveloped. In electronic textiles, this technique helps in the formation of conducting yarns. Zeng et al. (2013) have used wrapped conducting yarn for the formation of knitted electrodes. The core was segmented polyurethane, on which a silver-coated polyamide yarn was wrapped to transfer the generated current. Huang et al. (2008) have also fabricated a yarn based on a wrapping technique for a piezoresistive sensor.

9.7.1.2 Nanofibres/yarns

Nanoyarn is spun from powder- or solution-based polymers. It has superior functional properties, owing to high surface area. Lepró et al. (2010) have developed carbon nanotube nanoyarns from CNT forests grown on metallic substrates. They claim that the yarns have interesting electrical and mechanical properties and that they could be used for various structural applications in electronic devices (Bourzac, 2011).

9.7.1.3 Electro-spinning

A bi-component electro-spinning technique can produce core sheath structures, in which one type of material forms the core, and the other forms an outer shell. Several variations are possible, including having materials side by side, or one material in a different shape such as a star, pie wedge, sea island or even a custom design across the cross section embedded in an outer sheath.

9.7.1.4 Melt spinning

Melt spinning is a process of forming objects with a fixed cross section. The process requires the material to be passed through a mould or a die, forming a specific cross-sectional shape. The mould could also be reshaped to accommodate shapes having different core materials. Such bi-component fibres would be beneficial for producing crimp in some textile structures. Another important use of these materials is the manufacturing of non-woven fabrics where thermal bonding is required. Thus, when heat is applied, the outer material melts to form glue, hence bonding the web together. These structures could also be used to provide special core properties such as strength, conductivity, elasticity and comfort. Glauß et al. (2013) produced one such PVDF fibre with a conductive polypropylene core for energy-harvesting applications.

9.7.2 Piezoceramic fibres

Piezoceramic materials are chemically inert and physically strong. In fibre form, they have anisotropic structures. Usually, ceramic fibres are produced by the spinning of an organic or mineral precursor fibre, followed by heat treatment and pyrolysis (Hearle, 2001). Piezoceramic fibres comprising lead zirconate/lead titanate exhibit better sensitivity in terms of piezoelectric activity and elevated operating temperatures (Swallow et al., 2008). PZT fibres can be manufactured by various processes, such as sol–gel, viscous suspension spinning, extrusion and viscous plastic processing, some of which are already commercially available (Strock et al., 1999; Meyer et al., 1998; French and Cass, 1998; Meister et al., 2003; Bowen et al., 2006).

Generally, ceramic fibres are expected to have high strength and stiffness, and for this reason, they would be expected to be best suited for reinforcement of composite materials. Nevertheless, owing to superior electrical properties such as high dielectric constant, and high charge coefficient, such as in PZT, these materials could also be used for energy harvesting in fabrics. However, their rigidity, brittleness and, in some cases, environmental unfriendliness may inhibit their use in textiles.

French et al. (1997) have reported a method for producing continuous fine PZT filaments through a viscous-suspension-spinning process (VSSP). These continuous filaments can then be woven, wound or braided and are capable of producing large outputs from small volume fractions. These PZT fibres can be formed into 2D and 3D textile structures for their use in composites and other areas, such as vibration generation, transducers and others. These filaments are also capable of producing large output strokes from small volumes, due to the large extension ratio (20 μm per linear inch) of PZT.

Chen et al. (2010) reported production of PZT nanofibres aligned in interdigitated platinum wire electrodes. The structure was packaged in the soft polymer, polydimethylsiloxane (PDMS). When stress was applied to the polymer, a charge was produced between two electrodes, owing to bending and tensile stresses in the PZT nanofibres. The output voltage produced was 1.63 V, with an output power 0.03 μW.

9.7.3 Piezopolymer fibres

Polymeric fibres such as PVDF have the advantage of high flexibility, allowing them to be easily incorporated into flexible structures such as textiles for energy harvesting. PVDF is a lightweight, tough polymer and is available in a wide range of thicknesses. Although its thermal stability and electrochemical coupling coefficient is less than ceramics, it is still one of the most widely researched materials for engineering energy-harvesting fabrics. The working temperature of PVDF lies below 100 °C; however, new copolymers such as in polyvinylidenefluoride-co-trifluoroethylene [P (VDF-TrFE)] have been developed, extending the working temperature to 135 °C (Swallow et al., 2008).

9.7.4 Composite fibres

Piezocomposite fibres can be embedded in polymer matrices to form piezo fibres with a conducting core, or a composite fibre consisting of many coated layers for energy harvesting applications.

Qin et al. (2008) have demonstrated a textile fibre-based nanogenerator by growing ZnO nanowires (NWs) radially around Kevlar 129 fibres, using a hypothermal method. The device works as a dual-fibre nanogenerator, with one fibre covered with ZnO NWs entangled around another fibre with gold-coated NWs. One fibre was fixed, and the other was allowed to slide over the other fibre. A short-circuit current and open voltage were obtained due to brushing motion between the two fibres. The authors claim that fibres with grown ZnO NWs can be used to fabricate an energy-harvesting garment. Also, the fibres when bundled could produce much higher outputs than the reported power density of 20–80 mW m^{-2}. The operating frequency of the device is also claimed to be very low, making it a viable energy harvesting device from low-frequency human movements, heart beats and so on.

Egusa et al. (2010) have developed a multi-material piezoelectric fibre consisting of shells of a 700-μm-thick layer of P(VDF-TrFE) and 250-μm-thick layer of carbon-loaded poly(carbonate) (CPC) assembled with indium filaments and a poly(carbonate) cladding. The fibre can be used for communication applications as well as for energy harvesting.

Siores et al. (2010) have developed a fibre structure that can be used to convert mechanical and light energy into electrical energy. The hybrid energy conversion device consists of a piezoelectric polymeric structure coated with a photovoltaic system. The fibre is claimed to be flexible enough to be converted into textiles for energy harvesting.

Glauß et al. (2013) have reported the development of a PVDF fibre with a conductive core. The melt-spun bi-component fibre consists of a conductive polypropylene core (containing a 10 wt % carbon nanotubes and 2 wt% sodium stearate (NaSt)) covered with a PVDF sheath. The piezoelectric effects are achieved by draw winding, which favours the all-trans β phase formation.

Liu et al. (2013) have investigated the mechanical strength and piezoelectric characteristics of a PVDF/MWNT nanofibre developed using the near-field electro-spinning technique. They have reported that the fibres formed by this method have excellent structural stability, enhanced flexibility and a high piezoelectric strain coefficient (d_{33} 57.6 pm V^{-1}).

9.7.5 Piezo fabrics

9.7.5.1 Types of manufacturing techniques

Various textile structures can be employed to design a garment for embedded wearable technology. Fabric structures such as woven, knitted, braided, non-woven and other textile structures are possible, depending on the requirements of the system. Each type of system has its unique properties that can play a major role in the functionality of the system. Most of these types of textile structures are used for electronic textiles, such as embroidery and others. Nevertheless, these structures find uses in many smart textiles used today.

A woven structure offers high strength and stability when compared with other structures. Woven structures can be single, double or multilayered fabrics. Hence, a woven fabric can be engineered to achieve desired characteristics such as tensile strength, tear strength, shear strength, air permeability, drapeability, air and water absorbency, crease resistance and many others (McCann and Bryson, 2009).

Knitted structures are made of loops of yarn interconnected with each other. The size of the loop can be altered to produce a fabric as per required characteristics. Some knitted structures offer robustness and are suitable for many technical applications. Knitted structures are mainly classed as weft knitted or warp knitted. Weft-knitted fabrics are highly stretchable and hence are extremely useful for undergarment and sportswear production. Warp-knitted fabrics do not unravel as easily as weft-knitted structures, and have significant insulating properties. In piezoelectric harvesting textiles, knitted structures offer extensibility, which is advantageous for wearable piezoelectric textiles, allowing wearer comfort.

Non-woven structures can be employed in manufacturing smart textile structures. Non-wovens are classed according to their type of manufacturing. The three main processes involved in non-woven making are web formation, web bonding and finishing. Non-woven structures offer high absorbency, which accounts for their enormous use in the medical industry. For piezoelectric textiles, these structures could provide higher surface areas, resulting in increased power density.

Structures such as braided, tufted, felt, film, foam, laminated, bonded, stitched-through, net, embroidery, quilt and laced structures can also be formed. Textile composites and fibre-reinforced composites are another form of textile structures, consisting partly of textile materials (Corbman, 1983).

A composite structure can be formed with more than one component, such as non-woven and knitted structures, which combine the best features of both types of assemblies to address specific application requirements, such as enhanced performance characteristics, higher power output, device functionality, wearer comfort and more. Yet the optimal integration of piezoelectric fibres in a wearable fabric for maximum energy output remains to be established. To date, numerous knitted, woven, non-woven and composite structures have been employed to produce energy-harvesting fabrics. However, Vatansever et al. (2011) suggest that weaving is the best possible method of fabric production for smart textiles. Using piezoelectric, conductive and conventional textile fibres, different arrangements of warp and weft yarns are possible for the production of suitable woven fabrics. However, the conductive fibres must interweave with the same pole of piezoelectric fibres in order to avoid a short circuit. The woven fabric suggested by Vatansever et al. (2011) can be used to harvest energy using mechanical stress and strains.

Magniez et al. (2013) have demonstrated a method to produce piezoelectric woven fabrics from melt-spun PVDF fibres, which were spun using a Busschaert bi-component extruder. The PVDF fibres were assembled with conductive fibres and were integrated into various woven structures, such as plain weave and 2×2 twill weave. A non-conducting nylon yarn was used as insulation between two electrodes to prevent short-circuiting. The warp yarns were PVDF, and the weft yarns were silver-coated nylon. The fabrics were tested for electrical output using a 70 N impact force at a 1 Hz frequency, and a maximum output of 6 V was produced.

Bai et al. (2013) have also demonstrated woven nanogenerators made from ZnO NWs as warp and ZnO NWs with a Pd coating as weft. The Pd-coated wires are attached to a slider, while the other wires remained fixed. As the slider moves, the nanowires on fixed wires are deformed by friction, causing a peak output electrical current of about 17 pA.

Soin et al. (2014) have produced a 3D-knitted spacer piezo fabric. Melt-spun PVDF yarns as spacer yarns are incorporated between two knitted faces made of silver-coated polyamide yarns. They claim the piezo fabric that can produce a power output density of 1.10–5.10 $\mu W\,cm^{-2}$ at applied impact pressures in the range of 0.02–0.10 MPa.

Fang et al. (2011) have demonstrated a simple, efficient, cost-effective and flexible set-up to produce piezoelectric fabrics through an electro-spinning process. A PVDF solution comprised of PVDF pellets in dimethylformamide (DMF) was electro-spun at 15 kV to produce a nanoweb. The nanoweb was sandwiched between two aluminium electrodes to obtain an output voltage. Under 1 Hz compressive impacts, the average peak voltage output obtained was 0.43 V. When the impact frequency was increased to 5 Hz, the voltage output became 2.21 V. A further increase to 10 Hz produced a higher output voltage of 6.3 V.

Apart from manufacturing piezo fabric through the above-mentioned textile processes, various materials and/or structures could be combined to produce composite fabric assemblies. Such a structure could be a sandwich structure, with one layer being an energy-harvesting assembly and the other layers functioning as a current collector, reinforcement or insulation assembly. The piezoelectric fibre composite developed by Williams et al. (2002) is comprised of piezoelectric fibres such as those produced by Cass et al. (2003), impregnated in a polymer matrix. This composite resulted in superior properties and higher efficiency due to increased surface area.

Zeng et al. (2013) have demonstrated a fibre nanogenerator made from a PVDF-$NaNbO_3$ nanofibre non-woven web, which is capable of generating a peak open-circuit voltage of 3.4 V and a peak current of 4.4 μA in a cyclic compression test. The non-woven web was sandwiched between elastic-conducting knitted fabrics made from segmented polyurethane yarns wrapped with silver-coated polyamide multifilament yarns. The whole device was packaged between layers of polydimethylsiloxane to enhance its mechanical robustness.

Swallow et al. (2008) have reported the formation of a piezoelectric fibre composite-based energy harvesting device intended to be used as a glove for tremor suppression. They have investigated the use of both PVDF and PZT in fibre composites for the production of electrical outputs. The piezoelectric fibre composite containing PZT produced a power output of ~11 μW, compared to the power output of 0.3 μW of the PVDF material alone.

9.7.6 Optimisation of fabrication for wearable energy harvesting

Designing a wearable electronic device is a complex exercise. Depending on its intended end use and the technology to be incorporated, several factors have to be considered. In order to meet the needs of the end user, expertise from textile specialists, modern day technologies and electronics, skills of clothing and fashion designers and eventually the capability of manufacturer should be brought together in order to utilise its maximum potential (McCann and Bryson, 2009).

Since its realisation in 1990s, wearable computing has come a long way. With the advancement of computing technologies, it seems that there are no boundaries. From health-monitoring devices, such as garment-based ECG (electrocardiographs) (Gopalsamy et al., 1999) and respiration and temperature monitors, to other wearable computing devices, such as MP3-player jackets, textile keypads, electronic ski suits, smart shirts and many more, are applications that combine textiles with electronics (Meoli and May-Plumlee, 2002). The terms e-textiles, smart textiles, wearable electronics and Textronics are some of the terms used to describe such kinds of devices. Smart textiles for wearable technology utilise a number of recent developments that make it possible to incorporate electronics into textiles. Conductive textile materials are one example of a new technology that is widely used in these applications. Conductive textile materials, including conductive fibres, yarns and fabrics, are commonly used for flexible sensors, electromagnetic interference shielding, dust- and germ-free clothing, data transfer in clothing, as well as camouflage and stealth technologies for military applications. Conductivity in textiles is imparted by the addition of carbon, steel, nickel or silver, in the form of wires, fibres, or micro- and nanoparticulate matters. Conductive polymers have been developed by the processes of solvent spinning, solvent casting or spinning as blends with conventional polymers. They can be used as coating materials, or embedded particles in fibres. A more recent focus has been on the use of conductive inks, which can be employed to impart conductivity to specific areas on a garment. Conductive particles such as nickel, silver, gold, carbon and copper can be added to conventional inks, which can then be used to form patterns by using various printing techniques.

The use of flexible sensors in wearable electronics has reduced discomfort while wearing the garments. The size of the sensors can now be reduced, particularly with the advent of microtechnologies and nanotechnologies. Flexible sensors also are very suitable when the contact surface area is of prime importance. Optical fibres or conductive fibres embedded within a fabric can be useful for wireless technology integration in the textiles for data transfer, as they are unaffected by electromagnetic radiation and do not generate heat. As conventional batteries are bulky, there was a need to develop some alternate forms of energy sources for these devices. Solar cells have now been developed that utilise textile materials as the substrate. Some recent researches utilizing piezoelectric materials to harvest energy are also underway (Tang and Stylios, 2006).

As new technologies are being introduced, the problems associated with the design of wearable electronic devices are also evolving. The major problems that occur in designing wearable electronics include the incorporation of electric junctions into the device when a garment has to undergo processes involving mechanical stresses, washing, ironing and some other threats such as moisture, sweat, temperature, light, some chemical substances, dimensional changes and creasing. The electric supply to a device is also a major problem, as traditional batteries are large and heavy. On the other hand, ambient energy sources such as photovoltaics, thermogenerators and piezoelectric devices have small capacity. Hence, it is necessary to develop systems where these problems can be overcome to produce an ideal smart textile complying with the comfortability and functionality of the device (Gniotek and Krucinska, 2004). The connections in integrated circuits in textiles also need to be modified to overcome the problems mentioned above.

In designing wearable devices, there are several factors to consider. The main focus should be that it does not hinder the wearer's movements, unless intended for that purpose. Other important factors include the service life, reusability, the element of design, comfort level and functionality. Garment comfort and appearance is highly affected by the placement of the components. Table 9.2 shows a summary of design guidelines for wearable systems.

Whenever a garment is designed for many different wearers, the knowledge of diverse sizes and shapes is required. Some of the areas in human body are quite feasible for placement of additional components on the body such as non-moving parts with large surface areas. The additional components should be designed in such a way that they do not have any sharp edges and conform to body contours. The components should also have minimal weight to reduce discomfort. Similarly, the design must allow unrestricted movement of limbs and other parts of the body. Any special requirement such as the case where the user has to interact with an extreme environment has to be kept in mind when designing such apparel (Hännikäinen, 2006). It is also feasible to utilise places on the body such as wrists to place heart beat sensors (Martin, 2002). A new class of intelligent textiles has been suggested by Lymberis and Paradiso which utilises the neural networks for 'event prediction', generating alert signals for integrated communication wearable systems (Lymberis and Paradiso, 2008).

Table 9.2 Design guidelines for wearability

Guidelines for wearability	
Placement	Explains where extra components should be placed on body
Form language	Defines shape for additional components
Human movement	Considers the dynamic parts of human body structure
Proxemics	Perception of space by human brain
Sizing	Should be able to fit a number of users
Attachment	Extra components that can be fixed to the body comfortably
Containment	Considering what is inside the form
Weight	Balance across the human body; should not hinder human movement
Accessibility	Additional components should be easily approachable
Sensory interaction	Active or passive interaction between user and component
Thermal	Thermal comfort to the wearer
Aesthetics	Appearance or perceptual appropriateness
Long-term use	Effects of prolonged use on the body and mind

Adapted from Gemperle et al. (1998).

9.7.7 Testing of piezo fabrics for energy harvesting

Since their discovery, piezoelectric films, fibres, fabrics and others have been investigated for their outputs via different methods. The testing methods vary in terms of the intended end use, type of force applied and fabrication method.

Most commonly for shoe inserts, it is understood that the heel strike would mimic the impact of force acting on a body. Therefore, impact testing is one of the most preferred test methods for energy harvesting. It has also been used to test the effect of force applied on the output power in piezo fabrics (Magniez et al., 2013). Vatansever et al. (2012a) have used an Instron with a drop weight of 1.02 kg at several different heights to test the voltage output by a piezoelectric fibre composite.

Dynamic-impact force pulses produced with restrained pulse pressures and a range of frequencies can be used to investigate possible power outputs (Zeng et al., 2013). Soin et al. (2014) designed an experiment where they used an Instron system compression test by attaching a compression plate to the load cell. The impact pressure applied was in the range of 0.02–0.10 MPa, which generated an output power density of 1.1–5.1 $\mu W\ cm^{-2}$.

Apart from these popular tests, Yun and Yun (2013) have used a method in which they stretched a woven PVDF fabric. The fabric was fixed at one end, and the other end was mounted on a custom-designed linear actuation system. The movement of the actuator system was controlled using a stepper motor, which controlled the distance moved and the operational frequency. An oscilloscope was used to record the output voltage. It was claimed that a peak output power of 1.1 mW was achieved, using 20% stretching at 8 Hz ($\sim$0.63 $mW\ cm^{-2}$).

Fang et al. (2011) subjected their electro-spun PVDF fabric to 5 Hz repeated compressive impact and release cycles. They received steady outputs and also observed that with the increasing impact frequency, the output voltage increased. Yang and Yun (2012) produced a flexible, wearable shell structure using PVDF in fabrics. Because the intended application of the device was for elbows and fingers, they applied bending forces to the structure through a custom-designed linear actuator system. The bending angle was constant at 80°, and the folding and unfolding frequencies were 2 Hz.

9.8 Applications

9.8.1 Energy requirements

In recent years, there has been a significant increase in demand for powering *on-person* devices. As the sizes of these devices shrink, the energy requirements have also been reduced. This miniaturisation has also encouraged the emergence of embedded wearable applications. Hence, overall decreasing size and power requirements both present a feasible notion for energy harvesting using various power sources. Table 9.3 shows the energy requirements for several portable devices. It is worth mentioning that the requirements shown can vary depending on the manufacturer, model and usage. Some of the devices require only a few microwatts.

9.8.2 Feasibility of human-powered wearable devices

The ever-growing demand for green energy has made energy harvesting from renewable sources mandatory. The rapid increase in miniaturisation of electronic devices would mean that, in the future, the power requirement would go down to few microwatts. Hence, energy scavenging from microwatt-based generators could become

Table 9.3 Energy requirements for portable devices

Portable device	Power consumption	Energy autonomy
Quartz watch	5 μW	5 years
Cardiac pacemaker	50 μW	7 years
Wireless sensor node	100 μW	Lifetime
Hearing aid	1 mW	5 days
MP3 player	50 mW	15 h
Smartphone	1 W	5 h
Tablet (iPad)	1–2 W	24–48 h
Laptop	50–80 W	3–6 h

Adapted from Vullers et al. (2009) and Kintner (2012).

highly attractive. More important is the fact that the energy is not only renewable, but also available all the time, especially for handheld devices. This can be termed as ‘energy on the go’ and can be available in highly indigent circumstances.

The first device utilising human motion for energy scavenging was a self-winding wristwatch invented in the 18th century. Since then, energy scavenging has been utilised for watches for many years. Starner (1996) described the possibility of piezo energy harvesting through human motions. He reported that the simple human motions of walking produced about 67 W of energy. This ‘lost’ energy, with about 12.5% piezoelectric material conversion efficiency, could be translated into 10 W of power, which is more than adequate to power mW-based wearable devices. Since then, many studies have been carried out in an attempt to convert this ‘lost’ energy into usable electrical power. In human motion, energy also is available through other continuous and discontinuous activities, such as breathing and heart beat (Gonzalez et al., 2002). Breathing allows energy harvesting via exhalation as well as changes in chest perimeter. Changes in blood pressure and heart beat are another important source of energy harvesting for implantable devices such as pacemakers (Karami and Inman, 2012). Of all the discontinuous movements, walking provides maximum power outputs when compared to the rest of the body. This area has been widely explored by researchers.

Kymissis et al. (1998) integrated a PZT unimorph (a cantilever that consists of one piezoelectric layer and one inactive layer), a PVDF stave and a rotary magnetic generator into the heel of a shoe to harvest impact energy. They reported an output of 80 mW achieved using the PZT unimorph. Shenck and Paradiso (2001) also discussed the use of piezoelectric shoe inserts to produce energy. It is claimed that the upper limb movement could be used to harvest power up to 60 W (Gonzalez et al., 2002). Yang and Yun (2012) demonstrated a textile-based flexible energy harvester that can be worn on fingers and elbow joints. Waqar et al. (2013) also presented a parametric study of finite element simulations of piezo strips on fabric. Such fabric could be used to harvest energy merely from vibrations. Typing is another possible energy-harvesting source where impact energy could be transferred to usable electrical energy (Berridge, 2011). Bhaskaran et al. (2011) demonstrated a method to produce energy-harvesting keyboards and are working on integrating it into laptops using piezoelectric thin-film technology. Energy harvesting from peculiar sources such as ear canals have also been explored by some researchers, using flexible PVDF sheets. Delnavaz and Voix (2013) fabricated a device mounted in the headset and placed in the ear canal. The device deforms during mouth movements, giving electrical outputs.

Allameh et al. (2007) proposed to power a drug delivery system that delivers a drug to localised ailing cells. The system could be powered by the movements of body fluids or solids. Energy-harvesting tiles are now commercially available (http://www.pavegen.com/home) and are being installed at public locations such as train stations and other main transport hubs. Energy-harvesting tiles mounted at West Ham underground station in London generated enough power to light up the station. Energy-harvesting floors are already installed as dance floors in clubs such as Club Surya in London, which claims to be an eco-club (Henderson, 2009).

9.8.3 Medical and military wireless uses

There are numerous possible applications of energy harvesting through flexible textile materials. Edmison et al. (2002) described an initial prototype of a glove for user input that employs piezoelectric elements to sense the movement of the hands to illustrate the design issues involved in using piezoelectrics. Swallow et al. (2008) developed a microcomposite-based energy reclamation device for gloves. This non-invasive system can be used to harvest waste mechanical energy, which can then be utilised to suppress tremors using converse piezoelectric effect. If the tremor is not large enough to require suppression, the energy produced be directly stored in a storage device. A similar principle has been used by Zięba and Frydrysiak (2010) to measure breathing frequency and develop an energy-harvesting vest. Wang (2012) has also proposed harvesting respiration energy using piezoelectric polymer thin films.

Soldiers in the battlefield need energy to power up many accessories they carry. Wireless networking, such as cellular radio and satellite communications, requires a source or power. The weight of the batteries as well as their limited life are critical factors for a soldier who may be relying on batteries for communication, light, and in extreme cases, survival. Military equipment such as night goggles, GPS systems, radios and others all need batteries. Hence, a soldier may need to carry around 16–20 lbs (7.26–9.07 kg), as they are carrying a number of such devices (Johnson, 2012).

In such cases, energy-harvesting textiles could prove to be a major breakthrough. Advances in solar energy harvesting have proven helpful, as many companies are now trying to weave flexible solar panels into a soldier's uniform (Daileda, 2013; He et al., 2013). Yet it is stated that the power outputs could vary during the day due to a soldier's movements in a battlefield under shady areas. Conversely, a soldier could benefit from darkness at night and be even be more engaged. Being in continuous motion at all these times may provide a continuous source to harvest ambient energy. Furthermore, batteries are a finite source of power supply and could be worn out when needed most. Such an event in remote areas, or in the case of an unexpected prolonged stay in a certain situation, such as in warfare and catastrophic circumstances, could prove to be life-threatening. Energy-harvesting textiles could be employed independently or in addition to flexible solar panels, increasing the amount and availability of energy. Energy-harvesting knee braces (http://www.bionic-power.com/) and shoe inserts are also available.

Granstrom et al. (2007) have proposed an energy-harvesting backpack, capable of generating 45.6 mW of power output. The backpack has flexible PVDF films integrated into the shoulder straps, used to convert mechanical strain into electrical output.

Antennae can be integrated into a person's clothing (Massey, 2001). Such a system could be utilised for obtaining locations on a soldier's movement. It is also extremely useful for people working or holidaying in remote areas. The antenna would require only a small amount of energy and could be powered with human movement through piezo fabrics, hence providing location signals at all times.

In the medical field, many textile-based devices using piezoelectric materials as sensors and actuators have been developed. A medical ECG chest, sleep monitor, patient care tremor suppressor, and breast cancer detection bra are some of the many devices that employ various forms of piezo materials. Several portable types of health monitors are used for observing patient conditions. Such devices constantly need a power supply. The weight and limited life of batteries could prove to be life-threatening in some cases. Another important concern is the toxicity of these batteries (Bernardes et al., 2004). The battery systems contain electrolytes, which especially in the case of lithium batteries, are mostly toxic and flammable. Recycling these batteries could provide benefits, as suggested by Bernardes et al. (2004), but for applications such as those described above for military personnel and medical applications, it is not feasible. In these events, energy scavenging through human motion could potentially eliminate the need for battery systems and provide an efficient and reliable power source.

9.9 Future trends

There is a genuine need for energy harvesting for on-person wearable devices. Recent developments in piezo fibres, fabric architectures, piezo properties and others present a promising future for powering electronics. Metal powders, nanowires, nanotubes and copolymers have already been used to enhance piezoelectric properties. There are still possibilities of exploring other organic and inorganic materials producing hybrid piezoelectric structures to improve piezo properties. Another focus is on reducing toxicity from these fabrics, such as lead (e.g. PZT), which has made materials like PVDF a significant alternative option. Several researches have been conducted on the production of piezo fibres, using various processes for energy harvesting, such as melt spinning, electro-spinning and others. The focus currently is on faster, cheaper and more reliable methods for the production of piezo fibres, and the corresponding piezo fabrics.

Further work will continue to enhance the dielectric constants of materials used for piezo fabrics; improvements in fabric architecture and the easy integration of these piezo fibres with other flexible conductors, as well as sensing and actuating fibres. These developments can lead to a whole new generation of smart fabrics which could ultimately reduce the need to carry parasitic batteries, especially for on-person, low-power devices.

There are still problems regarding the durability, laundering and robustness of piezo fabrics. Zeng et al. (2013) have claimed to enhance the durability of piezo fabrics by encapsulating the whole structure in polydimethylsiloxane packaging. If somehow the whole piezo fabric could be made washable without damage, it could bring the next breakthrough in piezo fabric energy harvesting and its integration into smart textiles.

Another important research area that requires further exploration is standardisation of testing of these fabrics. Most researchers so far are using different testing methods for investigating electrical output. The locations of these fabrics on a person and how much strain is imparted in various body locations will be some of the factors dictating the outputs.

Due to ever-increasing user demand for wearable electronic gadgets and decreasing power requirements for these devices, a much-needed approach is for textile technologists to work closely with electronic manufacturers in order to make both worlds compatible. Multi-disciplinary teams consisting of designers and engineers could provide productive results that could change the functional profile of textiles. Working closely with end-users and understanding their needs (such as military personnel, peers, family, older people, and patients) would also help R&D providers to shape their lifestyle by designing fabrics to meet their aspirations.

Finally, the ultimate goal would be the adaptability and user-friendliness of these fabrics, in which form and function are integrated. In addition, size, shape, proportion, comfort and fit, combined with the overall aesthetic style of the fabrics, are achieved.

9.10 Conclusions

Since the discovery of piezoelectric effects in the 19th century, much progress has been made towards the realisation of their uses for viable energy generation. One of them is the development of piezo textiles for energy harvesting. From piezo fibre development, such as piezopolymers, piezoceramics, and composite fibres, to hybrid piezo fabrics incorporating electrodes and piezo, insulating and conducting fibres, the notion of a textile as a flexible material for covering the human body has been redefined.

This chapter has covered at length, the various aspects of piezoelectric energy-harvesting fabrics as an alternative power source especially for devices with low-energy requirements. Various developments in the field of energy-harvesting fabrics in terms of fibre production and fabric architecture have also been reviewed. Insights into existing and potential materials for these fabrics, and the design parameters for fabric architecture and garment production, have also been summarised. The feasibility of powering devices through human motion has been explored and is expected to become more focused with changes in lifestyles.

The need for powering on-person wearable devices can be easily addressed through textiles, which potentially could supply energy for data communications, health monitoring and emergency power supplies for survival and surveillance tactics in military and medical sectors. Moreover, portable devices such as mobile phones, notepads, GPS and others all need reliable, consistent and sustainable sources of power, especially as a backup in catastrophic situations. In such cases, energy-scavenging fabrics could provide an abundant source of power at any time of day (photovoltaics would only be active in daylight) as a standalone system, or as a part of an integrated hybrid power system incorporating a photovoltaic power system and storage media. These fabrics are envisioned to enhance the autonomy of end users in a power-dependent world.

Acknowledgements

The authors would like to thank the Australian Research Council (ARC) for its support of this research project through Grant LP110100455.

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