Conductive fibres for electronic textiles: an overview

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1.1 Introduction

1.1.1 Definition

Electrically conducting fibres have a surprisingly long history and have been used for aesthetics, anti-static and shielding purposes and for applications in electronic textiles.

A fibre may be defined as a structure that is fine, flexible and exhibits a high length-to-width ratio. A conductive fibre can be defined as an electrically conductive element having the structure of a fibre. Thus, a metal nail and thick copper wire are electrically conductive but not fibres, as they are neither fine nor flexible. In contrast, for the present purposes, a fine copper wire and silver-coated polymer fibre can both be categorized as conductive fibres.

The electrical resistance of metals is of the order of $10^{-5}\ \Omega$ cm, whereas that of a typical insulator would be $10^{12}\ \Omega$ cm. The electrical resistance of natural fibres is governed by the humidity of the air to which they are exposed (Murphy and Walker, 1928). For example, the specific resistance of wool varies from $1.6 \times 10^{9}\ \Omega$ cm at 53% relative humidity (RH) to 1.3×10^{6} at 86% RH (Marsh and Earp, 1933). In contrast, the resistance of polyester at 85% RH is greater than $7 \times 10^{12}\ \Omega$ cm (Hersh and Montgomery, 1952). At normal temperatures, the resistance of metals is proportional to the absolute temperature, whereas the resistance of insulators increases as temperatures decrease (Bardeen, 1940). The electrical conductivity of copper, silver and gold at 0 °C are 64, 66 and $49 \times 10^{-4}\ \Omega^{-1}\ \mathrm{cm}^{-1}$, respectively (Bardeen, 1940).

1.1.2 Archaeological metallized fibres

The first description of static electricity was by Thales of Miletus in the sixth century BCE (Noad, 1859), but the modern science of electricity was not formulated until the eighteenth century. However, electrically conducting textile fibres have a long history that goes back to antiquity. For example, gold-coated threads were produced in ancient times before the modern discovery of electricity but were, of course, designed for aesthetic purposes alone. In a story familiar to Homer, the adventurer Jason goes in search of a golden fleece (Rhodius, 3rd Century B.C.). Could this have been a reference to a fleece used to collect gold or to man-made gold fibres?

Historically, there have been various techniques for producing metal thread for textiles. Metals were hammered and cut into foil strips and then wrapped around a core.

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Figure 1.1 Silver-wrapped silk thread from the seventeenth century.
Figure supplied by Dr. Jane Batcheller of the University of Alberta.

Gold threads made by wrapping a flat ribbon of gold around a silk core are reported from a second century sarcophagus in Cyprus (Conroy and García, 2010). Alternatively, metal wires were wound directly around a core. In another approach, leather or paper was coated with gold leaf and then used directly, or again, wound around a core yarn (Hauser-Schäublin and Ardika, 2008). The techniques used often depended on the geographical origin. For example, metal-coated strips of paper were used in China, whilst hammered and cut strips of foil are reported from ancient Egypt and Persia (Hauser-Schäublin and Ardika, 2008).

A paper by Csiszár et al. (2013) describes manufacturing methods for metallized fibres made from the fourth century AD onwards. The metal strips were a few tenths of a millimetre in width and up to 70 mm in length. These might be wound around a textile core or used flat. Csiszár et al. (2013) also describe how silver gilt threads took over from gold around the first millennium. With reference to the literature, Csiszár et al. (2013) report that ~70 types of metallized thread are known.

Metal threads with animal hair cores are reported from around 1200 to 1300 AD (Skals, 1991). A paper on the cleaning of copper embroidery threads on an archaeological textile refers to a fabric embroidered with copper threads (Abdel-Kareem and Harith, 2008). Again, these were formed from solid metal strips wound around a cotton core that had been embroidered to produce a motif.

Details of gold and silver threads in Renaissance tapestries are reported by Hacke et al. (2003). Various metallized threads from the seventeenth and nineteenth centuries in South America are described by Muros et al. (2007). Figure 1.1 shows a seventeenth century silver-wrapped silk thread found in Dorchester in the United Kingdom.

1.1.3 Eighteenth century

After the modern discovery of electricity, various electrically conducting wires such as copper, iron, steel, brass, platinum, silver, German silver and gold have been used (Noad, 1859) in non-textile applications.

1.1.4 Nineteenth century developments

In the nineteenth century, the understanding of electricity was developed further. Michael Faraday, in his volume on experimental research in electricity from 1855, mentions the use of copper, iron, platinum and platina (natural impure platinum; Faraday, 1855).

Fibres specifically designed for electrical conductivity started to appear in the late nineteenth century.

Thomas Edison took out a patent for an electric lamp in 1880. The filament was made from carbonized cotton and linen threads, wood splints and paper (Edison, 1880).

The late nineteenth century saw the introduction of the first combinations of electrical functionality with textiles. For example, an electric corset promised to cure various ailments for 'ladies of all ages and all stations in life' (Fishlock, 2001), but the nature of the wiring is not clear. Considering the modern focus on powering wearable devices, it is notable that power was generated by the body using metal discs located next to the skin (Harness, 1891).

1.1.5 Twentieth century developments

The early twentieth century saw thinking focus on more practical combinations of electrical functionality and textiles. For example, a patent from 1911 describes an electrically heated glove (Carron, 1911) for 'drivers of aeroplanes, automobiles, motor boats and other conveyances which are guided by manually operated steering wheels'. It is proposed that the heating elements be made from German silver or other suitable wire. Another patent (Lemercier, 1918) describes the insertion of heating wires into gloves in a zigzag pattern to avoid breakage. The Second World War gave added impetus to the technology, as a patent for other electrically heated gloves for aviators demonstrated (Summers, 1945).

An important milestone was a patent from 1936 describing a method of producing multi-filament metal yarn (James et al., 1936). Another patent from 1936 describes heated textiles incorporating iron, nickel, chromium or stainless metal wires (Grisley, 1936). A further patent describes the use of nickel-chrome strips to electrically heat socks (Costanzo, 1936).

A major development was the discovery and development of conducting polymers by Heeger, MacDiarmid and Shirakawa in 1977 (Shirakawa et al., 1977). Heeger, MacDiarmid and Shirakawa won the Nobel Prize for chemistry in 2000 for their work (NobelPrize.org, 2014).

A patent for illuminated clothing (Schwartz and Meyer, 1979) suggests the use of a printed circuit sheet and 'electrical leads' as connectors. A patent (Courvoisier and Simon, 1987) describes a heating element for clothing where the heating element is a ductile metal wire, such as copper, coated with an insulating lacquer.

A review paper by Ghosh et al. (2006) gives an excellent description of the formation of electrical circuits in textile structures.

1.1.6 Recent developments

Smart textiles are expected to witness a 'staggering' growth in the coming years (MarketsandMarkets, 2013). The result of this renewed interest has been the expansion of commercial products and the development of new techniques for incorporating electrical functionality into textiles.

Modern approaches to the production of electrically conducting threads include conductive substrates, metal wires, metallized yarns and inherently conductive polymers. It is notable that some of the approaches hark back to the methods used in ancient times. For example, a patent from 2005 describes how an electrically conductive fibre can be wound around an elastic core to produce a yarn that can be elongated considerably (Nusco et al., 2005). Cottet et al. (2003) also report the use of copper threads following a helical path.

Some other methods have similarities to ancient methods where metallic surfaces are applied to strips. For example, a conductive bus structure created using Kapton strips with an 18-μm thick copper layer on top is described by Zysset (2013).

1.2 Types of conductive fibre

1.2.1 Substrates and conductive elements

A major modern use of electrically conducting textiles is in anti-static applications. Static electricity can not only be uncomfortable, but can also lead to fires and explosions (Kassebaum and Kocken, 1997). Anti-static properties can be conferred by coating fibres with metallized films, intrinsically conductive polymers, polyelectrolytes or by low molecular weight anti-statics in solution (Pionteck and Wypych, 2007). In the food industry, some solutions such as metal or metallized fibres are avoided because of the potential for contamination. Many of the technologies used for anti-statics have been employed for use in electronic textiles.

Electrically conducting fabrics can be created by the polymerization of pyrrole on a suitable substrate. The substrate provides the desired characteristics of flexibility, strength and processability. One application is in radar-absorbing materials for camouflage. Another application is in anti-static fabrics (Kuhn et al., 1995). Scilingo et al. (2003) report the production of polypyrrole (PPy)-coated Lycra/cotton fabric using a method based on a Milliken patent (Kuhn and Kimbrell, 1989) and a screen-printing technique. Approaches to coating fabrics with both PPy and copper are also reported by Gasana et al. (2006).

Another approach is to directly embed conducting elements within a fabric or yarn. For example, a Bedford cord can be used to surround electronic fibres (Nakad et al., 2007).

Woven, knitted and non-woven electrodes made from stainless steel fibres have been tested for functionality (Westbroek et al., 2006). It has been pointed out that damaged conductive fibres can lead to loss of electronic functionality. On the other hand, the large surface area and number of fibres offer the opportunity of fault tolerance (Cho, 2010).

Another approach to adding electronic functionality is to use conductive inks applied to a fabric (Parashkov et al., 2005). This can be applied using a variety of techniques, including screen printing (Paul et al., 2014).

A biochemical sensor based on a fabric is described by Zadeh et al. (2006). A flexible PPy fabric based on a nylon substrate is used.

1.2.2 Metal fibres

Modern polymers are very strong. For example, weight-for-weight nylon and the *para*-aramids are stronger than steel. However, most polymers are electrically insulating (Bakhshi, 1995). The advantage of metals is their very low electrical resistance. The resistance of typical metals is shown in Table 1.1.

A disadvantage of metal wires is that they have low elasticity and strength and can break (Cherenack and van Pieterson, 2012). Some metal-coated fibres and fabrics can corrode and crack after time (Buechley, 2007). However, the use of metal wires in research and the marketplace is reported. An early example of a modern electronic textile was the wearable motherboard first presented by Georgia Tech in 1998 (Park et al., 2002). Here, conductive fibres were woven into the fabric, creating a bus to connect conventional rigid printed circuit board (PCB) electronics. The results from the European Union (EU) projects MyHeart and BIOTEX demonstrated the potential benefits of electronic textiles. Here, electronics functionality was provided by conventional PCB modules located in pockets and connected by cables. The Adidas–Textronics miCoach sports bra uses conductive fibres knitted into the textile to form pulse-sensing electrodes (Adidas, 2015). The limitation of rigid electronics in flexible applications was addressed in part by the FP7 project STELLA. A key feature was the use of stretchable meandering copper interconnections (Gonzalez et al., 2008). The PASTA project developed an E-Thread® that provides a direct connection of two wire conductors to a chip (Brun et al., 2009).

There are numerous metal-based yarns on the market. For example, Bekintex (2014) markets Bekinox® stainless steel multi-filament yarns. Glenair (2014) markets ArmorLite™, a lightweight microfilament stainless steel braid. It is used as shielding in high-performance interconnect cabling.

In terms of application, a paper by Eichinger et al. (2007) describes the use of PCB design tools to convert an electronic layout to an embroidery pattern using Bekaert BK 50/2 conducting thread. Zhang et al. (2005) modelled the response of knitted fabrics

Table 1.1 Resistivity of metals (Chung, 2010)

	Resistivity at 20 °C (Ω cm)
Silver	1.59×10^{-6}
Copper	1.72×10^{-6}
Gold	2.44×10^{-6}
Iron	1.0×10^{-5}

made from stainless steel multi-filament yarns and compared the result to empirical data.

Fine metal wires may be directly integrated into the fabric or yarn structure. In some applications, there is a need to insulate the wires. This can be achieved by the application of an insulated coating. For example, Elektrisola Feindraht (2014) markets enamelled copper wire with coatings of polyurethane, polyesterimide, polyamidimide and polyimide.

Cottet et al. (2003) report the use of copper threads with diameter of 40 μm and insulated with a polyesterimide coating. The copper threads follow a helical path within the yarn in a similar manner as the one chosen by the ancients. It is reported that the thread can be used as transmission lines, with length for 10 cm and 100 cm for frequencies of 1.2 GHz and 120 MHz, respectively. Using wires of similar dimensions coated with polyurethane varnish, Locher and Troster (2007) report that transmission lines within a textile have a flat frequency response up to 2 GHz.

Swiss-Shield (2015) produces yarn with integrated metal wires for shielding. The surface can be either insulating or electrically conducting. Seashell Technologies produces silver nanowires of average diameters of 25–200 nm and lengths from 2 to 100 μm (Seashell, 2014).

Recently, fine polymer-coated copper wires have been introduced into the core of yarns (Cork et al., 2013) to power electronic components. Confining the electronics to yarns ensures that the required shear properties of a fabric are retained. When a textile fabric conforms to a shape, parts bend and other regions shear. Paper bends but does not shear, so it crumples rather than conforms to a shape. Keeping the electronic components and interconnects within yarns ensures that the electronics are not visible on the surface and that the textile retains its desired mechanical characteristics. An example of a garment produced using this technique is shown in Figure 1.2.

Figure 1.2 Garment with fully integrated LEDs.

1.2.3 Metallized fibres

Many of the first electronic textiles used Indian metal silk organzas (Buechley, 2007). These organzas are made from silk wound with thin gold strips to form a helix (Post, 1996), again in a method used by the ancients. Another approach is to add a metallized coating directly to a core yarn. In the commercial products, a number of base fibres are used. These range from cotton, silk, polyester and nylon to polybenzoxazole (PBO; Zylon®), aromatic polyesters (Vectran®) and aramids (Kevlar®).

Statex markets silver-plated polyamide yarns as Shieldex® in multi-filament or monofilament form (Statex, 2014). Syscom markets AmberStrand®, a metal clad fibre created using a PBO core (Syscom, 2014). The use of such fibres to produce an embroidered antenna is described by Seager et al. (2013). An embroidered antenna produced at Nottingham Trent University is shown in Figure 1.3. Syscom also produces a metal clad fibre using Kuraray's Vectran™ fiber (Syscom, 2014). Aracon (2014) produces metal-coated Kevlar® yarn. Coatings include nickel, copper and silver.

Quigdao Hengtong markets X-silver, a silvered fibre (Hengtong, 2014) aimed primarily at anti-microbial and shielding functions. Nobel Biomaterials markets ContaX, a multi-filament highly conductive natural silver-based fibre (ContaX, 2014) that is

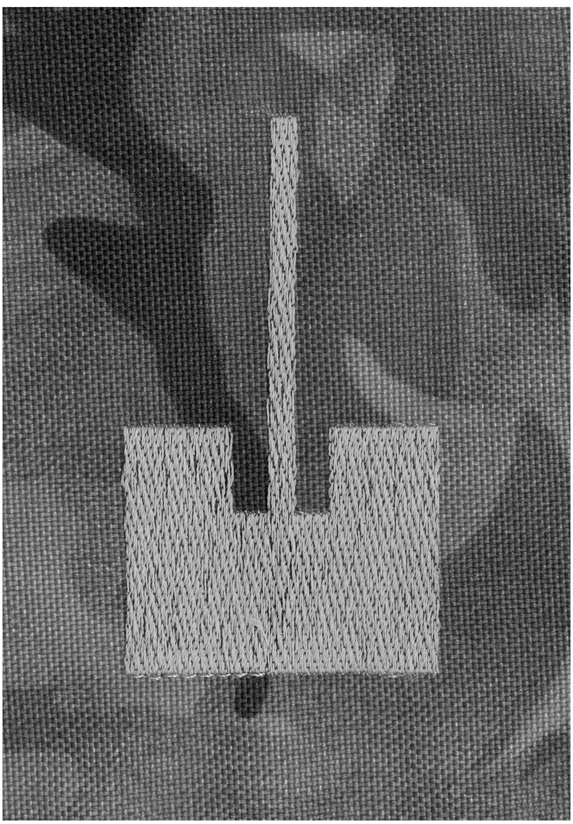

Figure 1.3 Embroidered antenna.

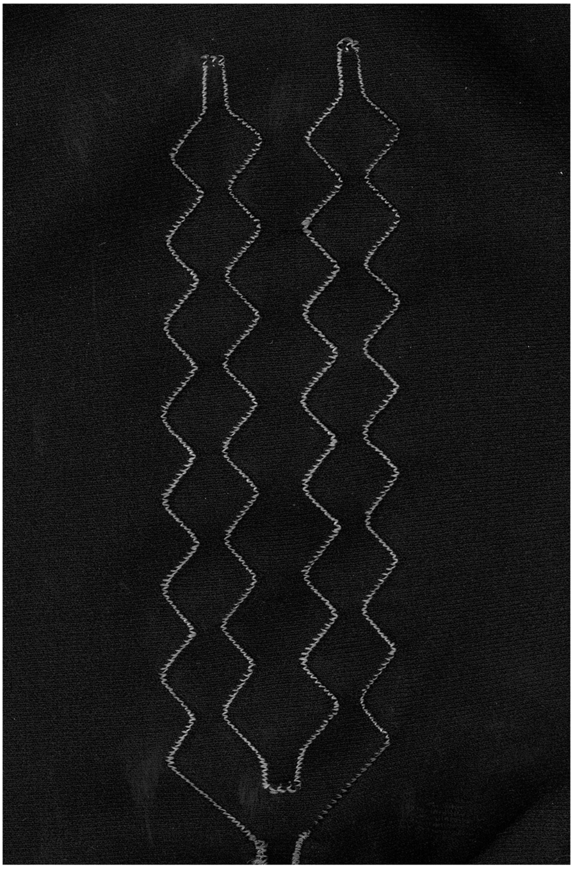

Figure 1.4 Stretch sensor knitted from silver-coated yarns.

used for anti-static functions. Noble Biomaterials also markets X-Static, a polymer fibre coated with metallic silver (X-Static, 2014). X-Static fibres are produced by coating conventional fibres with 100% surface area coverage of 99.9% pure silver. These are primarily marketed for their antibacterial properties.

R-Stat produces silver-coated polyamide yarns and stainless steel fibres. It also markets copper fibres where copper sulphide is suffused to the surface of polyester and polyamide fibres (R-Stat, 2014). Gold-coated *para*-aramid yarns produced through electroless deposition are described by Schwarz et al. (2010).

The use of silver-coated nylon has been utilized for the construction of knitted strain sensors (Atalay et al., 2013). Figure 1.4 shows a textile strain sensor created at Nottingham Trent University by incorporating silver-coated yarns into the structure.

1.2.4 Electrically conducting strips

The Wearable Computing Lab at ETH Zurich has developed a process for mounting devices on flexible plastic strips. The 2-mm-wide strips contain the metal bond pads and interconnect to link components and are woven into the textile in the weft

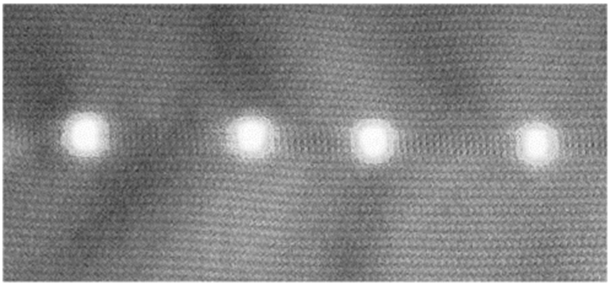

Figure 1.5 Illuminated plastic strips within a fabric.

direction in place of standard yarns (Zysset et al., 2012). In addition, an MIT report describes a textile-based antenna fabricated from polymer (PPy) strips (Pillai et al., 2010). In another paper, the functionality of Kapton strips coated with copper after bending is described (Cherenack et al., 2010).

Another approach is to print conducting lines onto insulating plastic strips. Figure 1.5 shows an illuminated fabric, created by Nottingham Trent University and the University of Southampton (Beeby et al., 2014), where light-emitting diode (LED) chips have been mounted on such a strip before embedding into a fabric. When not illuminated, neither the LEDs or strips are visible on either surface. Again, we see technologies similar to those used in ancient times, but with the ribbon substrate replaced with modern polymers.

1.2.5 Inherently conductive polymers (polyaniline, PPy)

There is increasing use of intrinsically conductive polymers in smart clothing as sensors and actuators (Cho, 2010). In 2000, the Nobel Prize in Chemistry was awarded jointly to Heeger, MacDiarmid and Shirakawa 'for the discovery and development of conductive polymers'. Their seminal work was published in 1977 (Shirakawa et al., 1977).

A patent from 1982 describes a treatment of acrylic and modacrylic fibres to produce a copper sulphide element that confers electrical conductivity (Gomibuchi et al., 1982). A patent from 1980 describes the use of copper iodide to produce an electrically conductive fibre without substantial colour change (Tanaka and Tsunawaki, 1981).

The production and properties of PPy are described in papers from McNeill et al. (1963) and Bolto et al. (1963). Electrically conducting yarns can be created using polyaniline (PANI) and PPy by either melt spinning or a coating process (Kim et al., 2004). The use of PANI is described in a recent review paper. PANI has low cost, good processability and good stability (Razak et al., 2014).

1.2.6 Introduction of conducting elements during extrusion

One method of producing electrically conducting fibres is to incorporate conducting particles during extrusion. A problem with this approach is that the incorporated particles can compromise the physical properties of the resultant yarn. Nevertheless, attempts have been made to incorporate metal particles, but these can cause abrasion to the spinnerette. Therefore, another approach is to use carbon. Epitropic fibres can be made by embedding tiny particles of carbon onto the surface of a fibre (Gibbs and Asada, 2004). Resistat (2014) markets carbon-suffused polymer fibres.

Another example where this technique is applied is FabRoc® yarn. EXO2 (2014) manufactures electrically heated gloves for the ski and motorcycle markets that incorporate the yarn. FabRoc is both flexible and electrically conducting and is formed into heating elements using the Thermoknit™ technology.

1.2.7 Conductive carbon nanotubes and fibres

Carbon nanotubes hold much promise but are currently very expensive to produce. However, researchers at Rice University have developed a carbon nanotube fibre (Behabtu et al., 2013). The fibre is produced using a wet spinning technique based on the short carbon nanotubes. Figure 1.6 shows the resultant yarn used to both power and support a light. A paper by Devaux et al. (2007) describes the preparation and properties of both conductive polymer-based fibres and carbon nanotube-based nanocomposite fibres.

Figure 1.6 Carbon nanotube fibre.
Figure supplied by Professor Matteo Pasquali of Rice University.

A review paper (De Volder et al., 2013) outlines past and future uses of carbon nanotube fibres, including incorporation into yarn.

1.3 Applications of conductive fibres

Electrically conducting fibres can be used for anti-static, anti-microbial, anti-odour, shielding and other applications. In electronic textiles, the conducting elements can provide power, deliver input and output signals or act as a transducer.

Transducers can be created by knitting electrically conductive yarns. Papers by Wijesiriwardana et al. (2003, 2004) describe the production of resistive, inductive and capacitive transducers using electronic flatbed knitting technology.

Knitting electrically conductive fibres can introduce some highly sophisticated functionality. For example, a paper by Tennant et al. (2012) describes methods for producing frequency-selective surfaces at microwave wavelengths. This was achieved using silver-coated nylon yarn on a polyester base. Alternatively, knitted conductive yarns can be used to create touch sensor switches (Wijesiriwardana et al., 2005) or knitted strain sensors for stroke rehabilitation (Preece et al., 2011).

A paper by Coyle et al. (2010) describes a number of biomedical sensors. A paper by Coosemans et al. (2006) describes electrocardiogram measurement using knitted and woven electrodes fabricated from Bekintex yarn.

A paper by Włókiennictwa (2004) describes the use of electrically conductive textiles as electromagnetic shields in physiotherapy where short-wave and microwave diathermies (electrically induced heat) are used.

Electrically conducting fibres can be used directly to measure strain. It is reported that PPy-coated Lycra compares well with sensitive strain gauge materials and inorganic thermistors (Cho, 2010). Mattmann et al. (2008) report a sensor thread made from a thermoplastic elastomer doped with 50% by weight of carbon black.

A range of sensor fabrics that came from the EU-funded projects Wealthy and MyHeart are described by Pacelli et al. (2006). Fabric electrodes created using flatbed knitting of stainless steel threads twisted around viscose or cotton yarns are described. Piezoresistive fabric sensors were created using Belltron coupled with Lycra.

Hertleer et al. (2004) describe a smart suit where stainless steel yarns are used to produce knitted electrodes (textrodes), a belt to detect respiration rates and an embroidered coil for a wireless link.

Added functionality can be conferred to electronic fibres. For example, the production of a drawn piezoelectric fibre is described and used to produce an optical resonator and a piezoelectric transducer (Egusa et al., 2010).

E-broidery, embroidery with conducting threads, is described by Post (1996) and Post et al. (2000). The sewability of various electrically conducting yarns is compared. Stainless steel threads have advantages because of their resistance to corrosion, biological inertness, availability in textile form and low cost. However, it is difficult to attach them to existing components. Composite yarns made from steel and polyester can be sewn by machine (Post et al., 2000).

1.4 Future trends

With strong growth expected in electronic textiles, it is essential that conductive elements meet not only environmental considerations, but also aesthetic and functional properties. Thus, ideally, electrically functional yarns and fibres should have the same diameters, moduli and strengths as conventional textile fibres. Doubling the fibre diameter increases the bending stiffness by a factor of 16, whereas doubling the elastic modulus simply doubles the bending stiffness (Ghosh, 2004). Another factor is the elastic recovery of fibres, although in many cases poor recovery of a fibre can be offset by the choice of fibre geometry within a yarn (e.g., spiral paths) and the inclusion of elastomeric yarns.

In some applications, such as wearables, the resistivity density product of the conducting elements might be important (Chung, 2010). For example, in power lines, aluminium is used because of its low density.

Electrically conducting fibres should be easily connected to other components and should be highly conducting with an insulated sleeve. They should be resistant to processing and, if required, be machine washable and robust to tumble drying. They should resist damage through fatigue, a major cause of fibre damage (Miraftab, 2009). Ideally, the fibres would also be dyeable. These requirements are almost certainly unachievable in the near future but could be considered long-term aims.

It is recognized that the recycling of textiles is an important factor and the introduction of electronics will present some challenges. Köhler and Som (2013) have pointed out that electronic textiles may result in adverse side effects during the life cycle of products. Conversely, the introduction of radio frequency identification devices into textile structures would aid identification of constituent fibre types and, after removal, lead to more accurate and efficient recycling procedures.

Despite environmental concerns, the use of carbon nanotubes in the correct context still has potential. Carbon nanotube wiring has the potential to create strong- and lightweight electrically conductive pathways and provide better transfer high-frequency signals (Lekawa-Raus et al., 2014).The first prototype carbon-nanotube computer has already been built (Kreupl, 2013) and promises to offer greater energy efficiency.

Graphene, the two-dimensional form of carbon, also shows great promise, and its study has attracted two Nobel Prizes and considerable research activity (Chabot et al., 2014). A report for the US Army Laboratory notes the potential for graphene in electronic textiles (Nayfeh et al., 2011).

Blue-sky thinking should consider exciting developments in superconductors. At very low temperatures, electrical conductors lose their resistance. Magnetic levitation is not possible with permanent magnets due to Earnshaw's law. However, levitation is possible using induced magnetism (diamagnetism), and the principle has been demonstrated (Simon and Geim, 2000). This requires very high magnetic fields, but it has been shown that a phenomenon called quantum locking can be used to levitate supercooled objects (Deutscher, 2013). Perhaps the latter technology could be used in the future to create levitating textiles for warehouse sorting, wireless hangers or in shop displays.

Developments in the understanding of quantum mechanics might have an effect on conducting elements in textiles. For example, quantum effects can significantly alter the electrical properties of a material. A 'quantum wire' where quantum effects predominate might not obey the classic formula for the resistance of a wire (Kumar, 2010):

$$R = \rho \frac{l}{A}$$

Moreover, single-wall carbon nanotubes can act as quantum wires (Tans et al., 1997). As electrical devices and their associated power lines get smaller, the lines must carry higher current densities that are predicted to approach the maximum achievable by metal wires. A possible solution might be carbon nanotube–copper composites that have the potential of offering the same conductivity as copper but with 100 times the current carrying capacity (Subramaniam et al., 2013).

Far into the future, technologies such as quantum wires operating at room temperature might transform the technology and open up unimaginable applications.

1.5 Conclusion

Electrically conducting threads were manufactured in antiquity before electricity was discovered. In modern times, metal wires, metal-wrapped yarns, metal-coated yarns, inherently conductive polymers and other technologies have been employed to confer electrically conducting pathways to textiles. Originally, conventional electrical wires were used, but then more sophisticated approaches were adopted. With the high growth in wearable devices and electronic textiles in particular, there will be an added impetus for the development of electrically conducting pathways with properties more in line with conventional fibres and yarns.

1.6 Sources of further information and advice

Excellent reviews of electronic textiles are provided by Cherenack and van Pieterson (2012) and Stoppa and Chiolerio (2014). The Conductive Fiber Manufacturers Council (2014) lists current manufacturers of conductive fibres. Products listed include nickel-, copper- and silver-coated Kevlar®, stainless steel wires and copper-coated polyamide and polyester fibres.

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