Integration of micro-electronics with yarns for smart textiles

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5.1 Introduction

Everyday clothing consists of fabrics whose primary purpose is both structural and aesthetic. Textile fabrics are created by binding fibres, and their functionality is defined by the yarn properties and the techniques by which the yarns are bound within the structure. The most popular techniques are

- 'Weaving', where fibres are interlaced orthogonally (Figure 5.1a),
- Interlooping of fibres, known as 'knitting' (Figure 5.1b).

Due to the physical binding of yarns, textile structures demonstrate good tensile recovery and shear properties, superior conformability, excellent skin contact (especially with knitted structures), breathability and comfort. As such, textile structures will provide an excellent platform for creating smart wearable systems.

Textiles can be enhanced with added functionality by the integration of information technology into the material that forms them. The vision of the Advanced Textiles Research Group (ATRG) at Nottingham Trent University in the United Kingdom, therefore, is to enable the introduction of electronically functional textiles and garments that can be cleaned and used without special treatments. The core aim is to integrate this new dimension of functionality into fibres, thus turning everyday objects into intelligent artefacts.

Most electronic textiles available today are made by attaching either permanent or removable electronic functionality. In the first generation of these systems, electronic devices were simply attached to garments or included in pockets. In the second generation, electrical connectivity and function were introduced by the inclusion of conducting yarns within the fabric structure. These applications are in general quite limited and act solely as demonstrations of the potential of integration that can be possible in the future. Integrating functionality into a flexible fibre form is thus the next logical progression in wearable textile electronics. The approach for realising this *fibre electronics technology*, however, requires a paradigm shift in conventional thinking.

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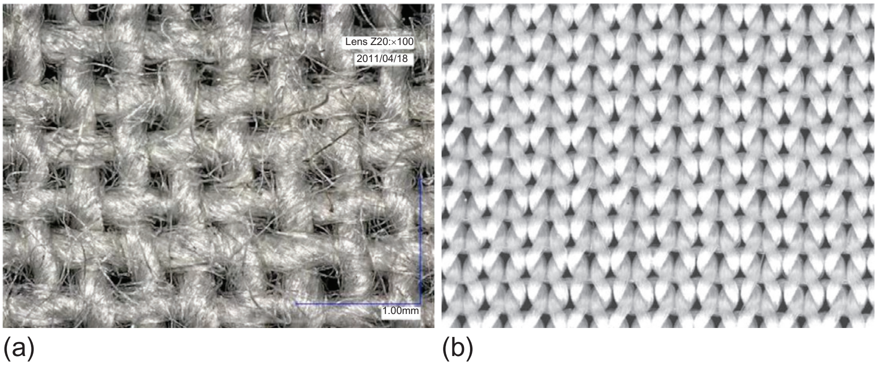

Figure 5.1 (a) Woven structure and (b) knitted structure.

5.2 State of the art

In the last few decades, many attempts have been made to integrate electronic functionality with textiles. Early medical sensing vests, for example, incorporated knitted electrodes for ECG monitoring, knitted stretch sensors for respiratory monitoring and piezoresistive motion detection (Paradiso and De Rossi, 2006; Dias et al., 2003, 2004); sweat-monitoring sensors were also located in a silicone patch that was subsequently mounted on the textile (Coyle et al., 2010). These examples were developed during the EU projects MyHeart and BIOTEX and demonstrated the potential benefits of the technology. However, electronic functionality was provided by conventional printed circuit board (PCB) modules located in pockets and connected by cables. Commercial electronically active textiles (EATs) offer similar limited integration of the electronic circuit functionality within the textile. For example, the Adidas-Textronics (2014) miCoach sports bra uses conductive fibres knitted into the textile to form pulse-sensing electrodes (NuMetrex, 2014). The electronic functionality is provided by a rigid (and potentially uncomfortable) snap-on module that attaches to the front of the bra and transmits the data to the receiver (e.g., sports watch, smartphone, cardio equipment).

The earliest example of electronic circuits in textiles was the wearable motherboard invented by Jayaraman at Georgia Tech in 1998 (Park et al., 2002). Stainless steel yarns were woven to create fabric with a data bus, to which conventional rigid PCB electronics could be connected at different locations. A similar approach has been adopted by Locher et al. (2004) to form a textile PCB using insulated conducting wires woven in both the warp and weft directions. In order to achieve the desired routing, textile vias were formed by selectively removing, by hand, wire insulation at the desired intersection and then depositing conductive adhesive. The most significant challenge faced by them was the mounting of electronic components reliably on the woven fabric. The FP7 project PLACE demonstrated the use of non-conductive adhesive to mount rigid modules (Von Ksrshiwoblozki et al., 2013). It is reported that the basic thermal and humidity testing showed good results, but mechanical and wash testing have been not performed. Furthermore, the electronics must still be mounted onto rigid interposers, and therefore the feel, comfort and appearance of the textile is severely compromised. The limitation of rigid electronics in flexible applications was addressed in part by the FP7 project STELLA. This project developed stretchable meandering copper interconnections and embedded ultra-thin silicon die in silicone (Gonzalez et al., 2011). These stretchable circuit boards consist of rigid islands and have to be subsequently attached to textiles, and the breathability and the shear behaviour of the textile fabric is compromised due to the use of silicones. This was followed by the PASTA project, which developed the E-Thread® that provides a direct connection of two conductors to a chip. The E-Thread® assembly can then be incorporated onto a yarn and subsequently woven or embroidered onto a textile fabric. E-Threads® with light-emitting diodes (LEDs) and radio frequency identification (RFID) chips are being commercialised through the Primo1D start-up, but the electronic components are visible on the yarn surface because they are not being integrated into the yarn structure. PASTA has also addressed more complex electronics, but these solutions use rigid crimpled flat packs with conventional PCBs (Brun et al., 2009).

The Wearable Computing Lab at ETH Zurich has developed a process for mounting small surface mount devices (SMD) on flexible plastic strips (Simon et al., 2012). The 2-mm wide strips contain the metal bond pads and interconnect to link components and are woven into the textile in the weft direction in place of standard yarns. Power is provided by connection to conductive threads located in the warp direction by bonding them together where they intersect. The use of standard bare die limits the degree of bending the strips can withstand, and the strips are not suitable for knitting or embroidery. The components and interconnects are left exposed at the surface of the textile and rapidly fail after washing (Zysset et al., 2012).

5.3 Fibre electronics technology

5.3.1 Background

The underlying core technology for clothing manufacture is performed in stages, with the most significant processing steps summarised below:

- *Fibre-assembling process*: during this step, a multitude of fibres are assembled to form a yarn.
- *Yarn-assembling process*: in this step, the yarns are assembled into a fabric, in order to create a textile fabric.
- *Fabric colouration and finishing process*: in this step, a fabric structure is given colour and/or better handling performance.
- *Fabric-assembling process*: in this step, the textile fabric is cut into shaped panels and sewn together to form a three-dimensional shell (i.e., a garment).

During all the above processes, fibres in yarns are subjected to three-dimensional flexure, including mechanical and physical effects due to bending, stretching, torsion and ageing effects (including long-time and short-time dependencies) as well as mechanical and electrical hysteresis effects. The objective of ATRG's research is to integrate semiconductor chips (packaged dice) with textile fibres in a manner in which the chips are protected from such negative influences. This objective could be achieved by either inserting the chip directly into a textile fibre or encapsulating the chip within a bundle of fibres; the two techniques are discussed below.

- *Inserting the chip into a textile fibre*: this can be achieved with only man-made fibres, by inserting the chip during the extrusion of the fibres. Although this technique can protect the chip from the tensile and bending stresses and the temperature, pressure and other chemical stresses to which the textile fibre will be subjected during post-processing, this method will not protect the chip from the torsional deformations of the textile fibre.
- *Encapsulating the chip within a bundle of fibres*: this method can protect the chip from all the aforementioned deformations and stresses, and it is not limited to man-made fibres. Therefore, the focus of the research is on creating the science base to populate a filament yarn with package dice and interconnects and to encapsulate the package dice with a polymer micropod. This process is based on the techniques and processes that are available in any semiconductor device/circuit fabrication area.

5.3.2 Development of the chip encapsulation technique

The concept is to integrate packaged dice (semiconductor chips) inside a bundle of fibres in a manner in which the chips are protected from all forms of mechanical, thermal and pressure forces. The solution is to position the chips inside a bundle of man-made filament fibres and then to encapsulate the area with a polymer matrix. In the following text, these notations will be used:

- The chip-encapsulated area as the Encapsulated Chip Area (ECA),
- The resultant yarn as the Electronically Functional Yarn (EFY).

The initial research focus was to study two possible approaches for creating the ECA. The first approach is to bond the filament fibres with a flexible polymeric resin to hermetically seal off the chip area. The second method is to use a side-by-side thermal-bonding process, which would interlock the filament fibres, thus sealing off the chip area. The behaviour of the ECA would depend on the individual properties of the components, their relative proportions, the degree of homogeneity, the properties of the interface between the components and the rate of solidification of each component.

The ECAs are positioned at regular intervals along the length of the filament fibres, as shown in Figure 5.2. This concept would enable the EFY to be inserted during weaving and positioned during knitting.

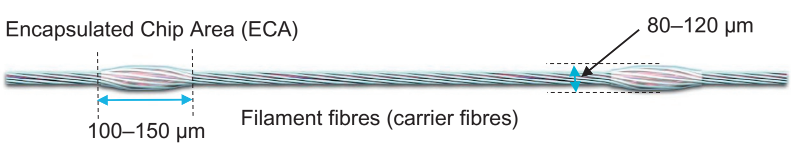

Figure 5.2 Core filament fibre populated with packaged dice and interconnects.

5.3.2.1 Side-by-side thermal-bonding process of filament fibres

In a side-by-side thermal-bonding process of filament fibres, heat energy must be used to melt the outer surfaces of the filament fibres to create a mechanically strong compound structure (ECA) to protect the semiconductor chip. The heat energy would cause greater molecule vibrations, until the molecules eventually would loosen from each other to form a liquid. At the melting point, the filament fibres that are in contact with each other would form strong bonds and encapsulate the chip, as shown in Figure 5.3.

5.3.2.2 Resin-impregnated ECA process

This technique has the advantage that all types of deformations and stresses to which the EFY would be subjected during textile processing (e.g., the day-to-day wearing of the garment (with the EFY) and its washing and ironing) can be endured by the filament fibres and the polymer resin. The polymer resin would also shield (seal off) the chip from liquids, dust and so on. The described concept would also enable fine copper wire to be incorporated into the EFY for powering the chip and signal transmission (Figure 5.4).

Of the two concepts described in Sections 5.3.2.1 and 5.3.2.2, the resin-impregnated ECA process is the preferred option, as the use of thermal energy to form the ECA by using side-by-side thermal bonding could result in damaging the functionality of the semiconductor chip.

The key research objectives were

- the development of the encapsulation technique,
- the modelling of the encapsulation process,
- the development of a technique of connecting fine copper wire onto solder pads of chips,

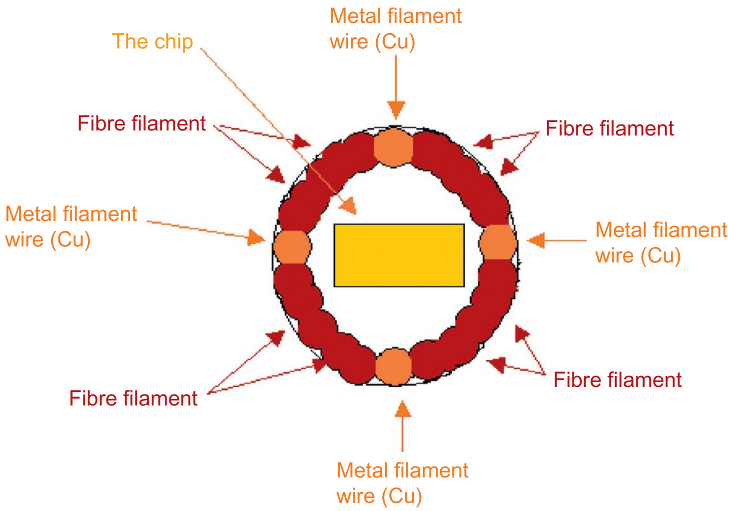

Figure 5.3 Schematic of side-by-side fibre bonding.

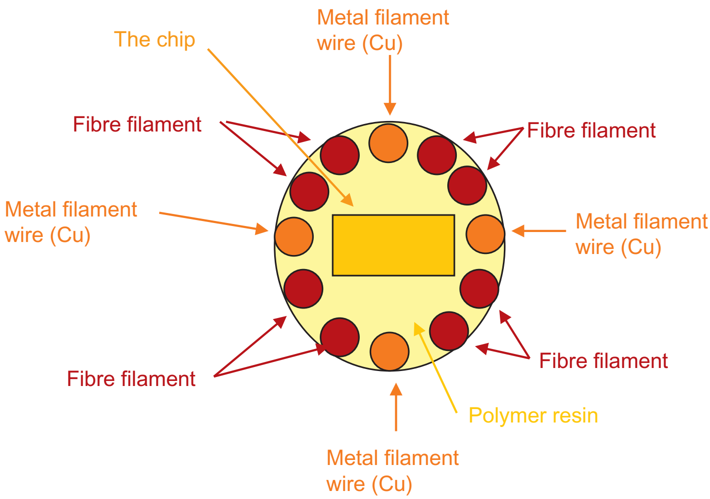

Figure 5.4 Schematic of resign-impregnated encapsulation.

- the development of an encapsulation technique,
- the evaluation of the fibre-encapsulated chip (i.e., for mechanical stresses).

The core technology platform developed to produce EFY is described below.

The technology developed is based on the concept of packaging the chip inside a bundle of fibres in a manner in which it is protected from all forms of mechanical, thermal and chemical stresses. The solution is to position the chip onto a core filament yarn and then to solder fine copper wires onto the solder pads of the chip. The diameter of the copper wire will depend on the solder pad dimensions. The chip is then protected by forming a polymer micro-pod around the chip. A schematic of the technology is shown in Figure 5.5. The micro-pods will form a hermetically closed seal around the chip, thus protecting it from all forms of stresses (thermal, chemical and mechanical). The micro-pod will also protect the solder joints from undue flexing. Between micro-pods the fibres of the yarn will be unconstrained, a feature that will help retain the textile characteristics of the yarn as a whole. Finally, a fibre sheath is formed surrounding the core filament yarn populated with semiconductor chips and the interconnects. This method would protect the resultant electronically functional yarn during weaving, knitting and sewing.

Several demonstrator yarns have been developed for different application areas:

- **Sewing thread with an electronic signature**: RFID chips are embedded within the fibres of sewing thread, which can then be incorporated into garments and leather products (handbags, shoes, etc.) for brand definition and protection, security, product identification, traceability, location definition and tracking (logistics). A major advantage of embedding RFID chips in yarn is that the antenna, which is essential for the working of the chip, can also be integrated within the fibres of the yarn. The smallest possible antenna developed so far is 80 times bigger than the RFID chip—a fundamental issue that can be resolved with RFID yarns.

The RFID-sewing thread was incorporated into the seam of a garment in order to study its durability on domestic washing machines and dryers.

- **Light-emitting yarn**: LEDs (1.00 mm × 0.50 mm × 0.15 mm) are encapsulated into polyethylene (PE) yarn; see Figure 5.6a. A textile garment has been produced with LED yarn as a working demonstrator (Figure 5.6b). Light-emitting yarn could be easily embroidered onto fabrics to create garments for promotional events and the movie industry; textiles embedded with LEDs for cyclists, pedestrians, kids, construction and road personnel; and soft toys.
- **Temperature-sensing yarn**: these are created by encapsulating thermistors (0.50 mm × 0.80 mm × 0.80 mm) in yarns. Application for these yarns will in medicine and health care, personal protection equipment and transport textiles.

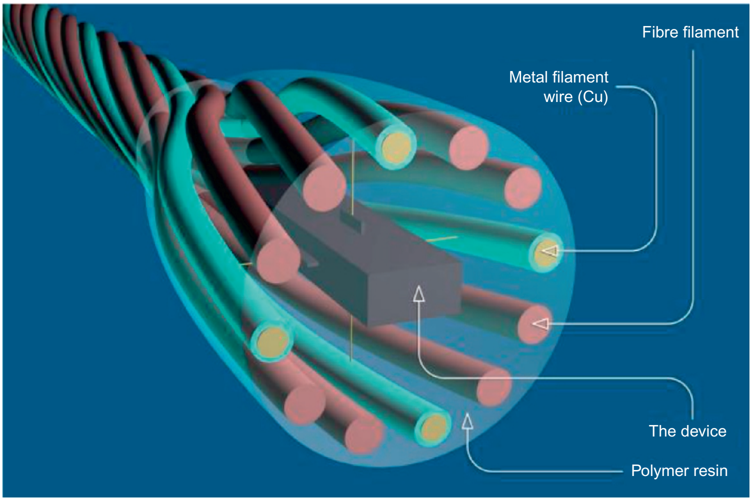

Figure 5.5 Schematic of electronic functional yarn.

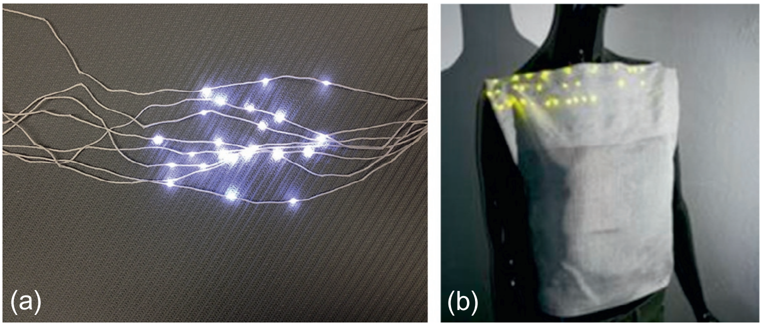

Figure 5.6 (a) LED yarn and (b) LED garment.

5.4 Summary

Growth in electronic textiles is strong, but at the moment, most solutions compromise the process of textile production and the textile performance. By fully integrating electronics into the heart of textiles at the yarn production stage, the aim is to facilitate the manufacture of a new generation of wearable electronic systems. Full integration will ensure that textile properties such as conformability and durability are retained. The knowledge generated and the technology developed will provide new products in new application areas. The technology will be cutting edge at a world-class level, offering economic benefits both to consumers and the industry.

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