Electronic Temperature Sensing Yarn

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***Abstract*— This paper reports the development of an electronic temperature sensing (ETS) yarn by embedding commercially available thermistors within the fibres of a yarn. The thermistor is initially soldered onto a fine copper wire and then encapsulated to form a polymer micro-pod. The micro-pod protects the thermistor from mechanical and chemical stresses. Thereafter the fine copper wire with micro-pods is covered by a tubular warp knitted structure to craft the final ETS yarn. The miniature size of the micro-pod makes the electronics invisible to the wearer. Such a yarn can be used to knit or weave any textile structure. It is also capable of providing temperature readings at a given point (localised) and can be used to make a wearable thermograph. Where the ETS yarn is included in a garment, it can be safely washed.**

Keywords— Wearable temperature sensor; fibre electronic technology; Wound temperature; contact temperature measurement; electronic textiles(e-textiles); Wearable sensor; Wearable electronics; electronic temperature sensing

I. INTRODUCTION (*Heading 1*)

Wound care has become one of the leading health challenges in the 21st century [1]. Wounds require frequent dressing changes, an activity which is a burden in terms of health care costs, nursing care, patient outcomes and hospital recovery time [2]. Normally waddings are made from textile fibres and are used in surgical procedures as wound dressings. The development of a textile based smart wadding capable of measuring the temperature of a wound continuously and remotely, without disturbing the wound site, would provide the clinical staff with a valuable tool to improve wound management and reduce the wound care costs.

Temperature is an established marker of infection in wounds [3][4][5]. For this reason, an electronic temperature sensing (ETS) yarn has been developed by incorporating thermistor chips within the fibers of the yarn. A heat conductive UV curable polymer resin was used to encapsulate the thermistor, giving it mechanical strength and ensuring washability of the yarn (tested up to 10 machine washes). The ETS yarn can be easily used to knit or weave a bandage or a wadding where, due to the miniature size of the thermistors used, it is not visible to the naked eye. Even though there are many wearable sensors available commercially, their dimensions make them easily identifiable by the wearer [6][7][8].

By using the Fibre Electronic Technology (FET) pioneered by Dias [9] where semiconductor dies are incorporated within the fibres of yarn, commercially available thermistors can be embedded within the fibres of a yarn. The FET consists of the following three key stages:

- Stage 1 – Interconnect formation – fine, insulated, copper wires are soldered onto the solder pads of semiconductor package dies (in this case surface mount thermistors), shown in Fig. 1a;
- Stage 2 – Encapsulation – the thermistor chip and solder joints are encapsulated to form a polymer micro-pod, shown in Fig. 1b;
- Stage 3 – Covering – a fibre sheath is formed around the interconnects and micro-pods to conceal them, protect from mechanical damage and provide additional strength to the fibre, shown in Fig. 1c.

This paper presents an in-depth exploration of each of the above stages.

II. MAKING OF THE ELECTRONIC TEMPERATURE SENSING YARN

A. *Stage 1 - Interconnect formation*

The creation of a robust and efficient bond between the solder pads of the microchip and copper wire (in this case a 50.0µm diameter single strand insulated copper wire) to form the interconnects is one of the key steps of the FET process. The research at Advance Textiles Research Group(ATRG) has demonstrated that a metal solder bond provides mechanically strong and electrically efficient connection between fine copper wires and the solder pads of packaged dice. To accommodate such small connections, a focused IR Reflow Workstation (IR-XT3M, PDR Ltd., UK) was used to form interconnects.

In order to hold the microchip and wire securely during the soldering process, a miniature mould was constructed using silicone and silicon carbide polymer. These materials were chosen due to their thermally conductive properties and the ease of moulding. The micro-mould was constructed by gluing the miniature thermistor chip onto a Perspex slide before forming a thin wall of clay around the thermistor microchip. Clay was used because it does not stick on to the silicone used in the mould. Equal volumes of silicone and silicon carbide powder were mixed with 10% platinum catalyst. After stirring the mixture carefully for three minutes, the solution was left in a vacuum chamber for five minutes to prevent air bubble formation in the mould. The mixture was then poured inside the clay walls and left to harden.

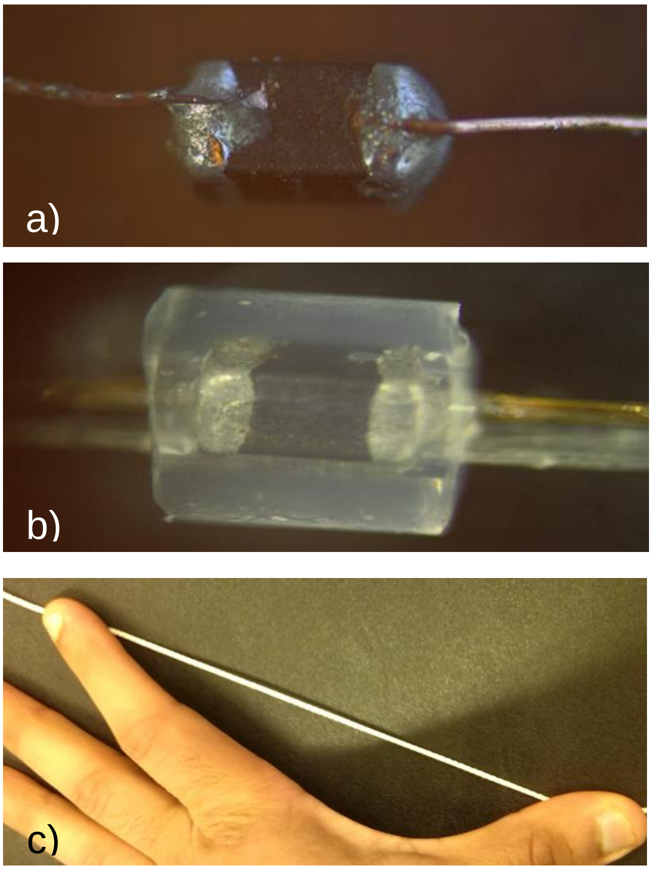

Fig. 1: *The three stages of the FET process: Interconnect formation (a), Encapsulation (b) and covering (c).*

The thermistor was positioned inside the micro-mould and 90µg of solder paste was deposited on each of the solder pads of the thermistor using a controlled solder dispenser (Ultimus™ I, Nordson EFD, RI, USA). The fine copper wire was then laid unbroken across the solder pads before curing the solder using the reflow work station as detailed previously (The end result is shown in Figure 1a). After completion of the soldering process the short circuit created by the length of copper wire remaining between the two solder pads was removed with a sharp blade. Since the blade could damage the silicon carbide mould during cutting, a second micro-mould was constructed using General Purpose Resin (GPR), which is a polyester resin in styrene solution ($C_6H_5CH=CH_2$, CAS No.-100-42-5, Stynolite, UK). GPR was chosen from a number of candidate materials, primarily because of its hardness. It should be noted that the second micro-mould could not be used to hold the chip during the soldering process due to the low thermal stability of the GPR. The GPR mould was constructed by gluing the miniature thermistor chip onto the surface of a silicone sheet. Since superglue does not adhere well to silicone, unhardened silicone mixed with 10% platinum catalyst was used as a glue to stick the thermistor chip on to the silicone sheet. Thereafter, the mixture was hardened using a hot air gun (HL 1810 S, STEINEL, UK). As with the silicone and silicon carbide mixture, the solution of GPR mixed with 2% methyl ethyl ketone peroxide as a catalyst, was left in a vacuum chamber for five minutes and then poured inside the silicone walls.

Two cymbal yarn tensioners were welded on either side of an aluminium rod to hold and control the copper wire during the soldering process. The two moulds were positioned between the two tensioners. To ensure that the copper wire is in contact with the micro-chip when it is positioned in the mould the two halves were fixed on to the aluminium rod at equal height. The copper wire is positioned in the tensioners as shown in Figure 2.

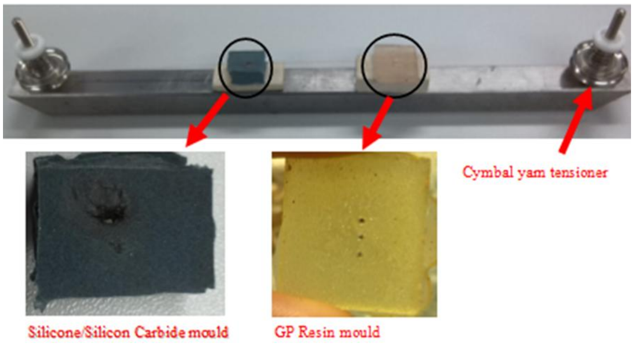

Fig. 2: *Soldering Jig designed for forming interconnects*

B. Encapsulation stage

The microchip thermistor and the solder bonds have to be encapsulated with a polymer micro-pod to protect against mechanical, thermal and chemical stresses to which the electronic yarn would be subjected during fabric production, garment manufacturing and later during its use. The micro-pod would also protect the microchip during washing, spinning and drying. As such the creation of the micro-pod is an important step of FET. In order to enhance the mechanical strength of the interconnects, the copper wire with soldered microchips were twisted with two 167dTex/48 polyester yarns and then the microchip was encapsulated with a thermally conductive resin. Two types of encapsulation material were tested (Multi-Cure® 9-20801 and 9001-E-V-3.5, Dymax Corporation, CT, USA). The resins were dispensed by using an EFD Nordson dispenser, and cured with an UV spot curing system, thus forming the micro-pod.

In order to control the volume and shape of the micro-pod; the thermistor microchip, interconnects and the two polyester yarns were placed inside a 1.0mm long hollow Teflon tube with a 0.8mm internal diameter. Thereafter resin was injected from the two sides of the tube taking care to avoid the trapping of an air bubble. A cylindrical shape was chosen for the micro-pod as textile yarns are generally of cylindrical shape. The minimum length of the micro-pod can be estimated as the length of the thermistor chip, Lc.

The internal diameter of the Teflon tube required to create the micro-pod was estimated by assuming that the two polyester yarns are placed on the two sides of the thermistor chip as shown in fig. 3. However, practically it is extremely difficult to align all the fibres of the polyester yarn to be on the opposite sides of the microchip.

In order to calculate the diameters of the two polyester yarns placed inside the Teflon tube for encapsulation, it was important to measure the diameter of a single fibre of polyester yarn. By considering the volume fraction of a yarn, the diameter of a single yarn (Dy) was estimated using the following equations

$$Vf = \frac{Area\ of\ fibres}{Area\ of\ yarn} = (\pi * \left(\frac{Df}{2}\right)^2 * nf)/(\pi * \left(\frac{Dy}{2}\right)^2) \qquad (1)$$

Therefore

$$Dy = 2 * \sqrt{(\left(\frac{Df}{2}\right)^2 * nf)/Vf} \qquad (2)$$

Where,

Vf- Volume fraction, Df- diameter of a polyester fibre, nf- number of polyester filaments in a yarn,

The diameter of a single filament of the polyester yarn was determined by using an Olympus BX41 microscope as 14.46 micrometres. The theoretical maximum volume fraction of a yarn is estimated as 0.785[10]. It was assumed that the polyester filaments were packed at a theoretical maximum to form yarn of cylindrical shape. By using the above values, the diameter of a single polyester yarn was calculated as 0.113mm with “(2),”. However, it should be noted that in reality, the volume fraction will be lower than the maximum and therefore the diameter of polyester yarn will be higher than the calculated value.

Hence the optimum diameter of the micro-pod, Dm, was calculated as 0.726mm using the following equation:

$$Dm = Dy * 2 + Wc \qquad (3)$$

Where, Wc is the width of the chip,

However, it was difficult to obtain a commercially available Teflon tube with an internal diameter of 0.726mm. As such a Teflon tube with an internal diameter of 0.8mm was used for the encapsulation process.

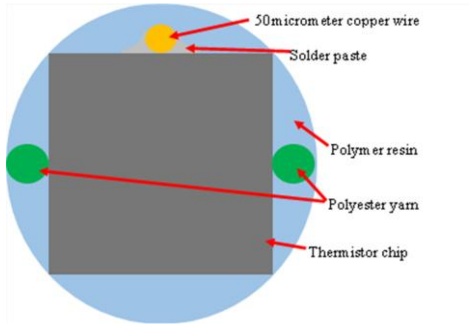

Fig. 3: *Cross sectional view of the Micro-pod*

C. *Covering stage*

The final stage of the electronic yarn manufacture is to surround the micro-pod, interconnects and PE carrier yarns with a fibre sheath, in order to protect the interconnects being damaged due to mechanical stresses during use. This was achieved with a small diameter circular warp knitting machine from RIUS, MC-2. The machine consist of a 10.0mm diameter hollow needle cylinder with six latch needles, and an inner diameter of 2.0mm. The latch needles were threaded with six 167dTex/48 polyester filament yarns The carrier yarn consisting of micro-pods, copper interconnects and two polyester yarns was passed through the 2,0 mm bore of the needle cylinder with six additional 167dTex/48 polyester filament yarns, in order to create a tight packing of carrier yarn in the resultant ETS yarn. This technique ensures that the electronic circuitry and interconnects are hidden within the resultant yarn, and also allows all types of textile fibres to be used to from the fibre sheath. The diameter of the resultant ETS yarn is around 1.9mm and it is defined by the dimensions of the microchip.

III. TESTING THE ETS YARN

It is important to the study the response of the ETS yarn to a change in temperature. Therefore, an experiment was carried out using the precision Electronic Hot Plate Model 1000-1 from Electronic Micro Systems Ltd. The temperature of the hotplate was set to a predetermined temperature and the ETS yarn was placed on the hot plate. Thirty seconds after the ETS yarn has reached the temperature of the hotplate it was removed from the hotplate and left in room temperature for cooling. The response of the ETS yarn is shown in Fig. 4 below.

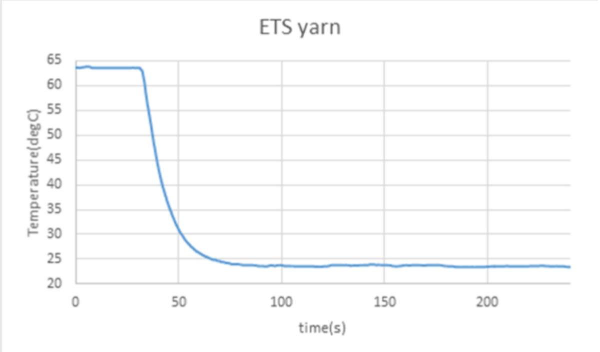

Fig. 4: *Response time of the ETS yarn*

The results as seen on the fig 4 shows that the yarn responds quickly to a change in temperature. It took the ETS yarn 49.0 seconds to record the room temperature. The above response time is acceptable to monitor the healing of a wound as the temperature of an infected wound would change much slowly.

A temperature sensing armband was knitted using four ETS yarns. The yarns were connected to an Arduino Pro Mini which was connected to an Arduino BlueSMiRF. This provided remote temperature measurements. A program in LabVIEW was developed to read the thermistor readings and display the output.

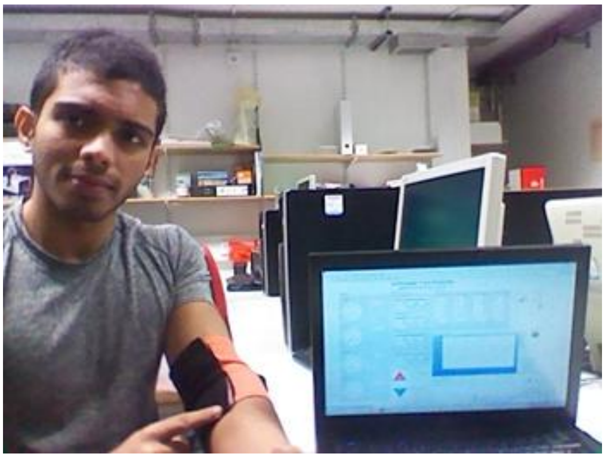

Fig. 5: *Armband knitted using the ETS yarn*

IV. CONCLUSION

It can be said that the ETS yarn could be used for making temperature sensing garments which could then be used for remote temperature monitoring. However it is important to automate the production of the ETS yarn in-order to make it commercially available.

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