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Computing Fibers: A Novel Fiber for Intelligent Fabrics?**

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This communication describes a possible path for transition from a wearable computer to a fiber computer in which digital processing power is integrated directly into textiles via circuits on individual fibers. Three different classes of computing fiber substrate (active, passive, and intermediate) are discussed and some technologies for their manufacture are reviewed. It is shown here that with two of these techniques it is possible to develop new substrates for the semiconductor industry. Using an silicon-on-insulator (SOI) process, polycrystalline silicon fibers with a length of 42 mm have been successfully produced at NMRC in Ireland. These fibers are 35 μm wide and 1 μm thick. Silicon carbide (SiC) and silicon dioxide (SiO_2) endless fibers (subsequently cut in to 20 cm lengths) have also been produced by extrusion. After sintering, this method yielded polycrystalline SiC fibers and pure amorphous SiO_2 glass fibers. For many future applications, fiber computing appears to be a possible key to success. The computing power offered by such fibers may be combined with additional in- and output functions by weaving fiber-based sensors and piezoelectric materials into textiles.

1. Introduction

Integrating electronics into ubiquitous or wearable systems started with packaged integrated electronic components (ICs) interconnected with each other on a rigid or flexible printed circuit board.[1–2] Enclosing these circuit boards in a hermetic package for protection from environmental effects is common practice. There are also more novel approaches towards integrating passive electronic components into objects, as demonstrated by Post and Orth.[3] In a move towards higher scale integration, they incorporated electrically-conducting stainless steel fibers into textiles for the purpose of connecting circuit boards. De Rossi et al.[4] used conductive polymers to impart sensor and actuator functions to conventional fabric by coating them with a thin layer of conducting polymer. The conductivity of this coating changed as a function of strain and temperature and a prototype glove made from this coated textile exhibited embedded sensing and actuating capabilities. Durry et. al. and others have worked with organic semiconductor microelectronic devices fabricated on flexible substrates.[5–7]

Given today's technology, it is possible to group the possibilities for integrating (micro)electronics into clothing at three levels.

- Garment level integration. At this level, the fundamental design of clothing and electronic components is accom-

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plished independently of each other and they are combined at a later stage.[1–2] A good example of this type of integration was the Philips–Levi ICD jacket, which is no longer available.

- Fabric level integration. The electronics are integrated into the fabric from which the garment is made. A good example is circuit boards attached to the fabric and connected to each other using conductive threads. Integration of electronic components such as sensors and integrated circuits are also examples that can be included in this group.[8–9] This provides a relatively unobtrusive way of integrating electronic components into clothing.
- Fiber level integration. Part or all of the necessary electronics, sensors, or actuators are directly integrated into the fibers that make up the yarns and subsequently the fabrics.

Today, with the exception of the use of conductive threads/yarns[3,8] and sensors,[4] examples that are based on the use of fibers for electronics are rare and it is clear that the opportunities at this level have yet to be thoroughly explored. In this communication we focus on the possibilities of microelectronic textile integration at the fiber level.

The word “fiber” is a generic geometric term describing a material having very long length compared with its cross-sectional dimensions: possessing a very high aspect ratio. Human hair is a good example with which to visualize this geometry. Fibers are used in many different areas of industry, from textiles to optics to advanced composite materials. In ordinary daily life, we interact with many objects that are either made of fibers or contain fibers in their structure, ranging from soft textiles such as clothes, curtains, tablecloths, towels, to rigid structures such as tennis racket frames and car body panels. The fibers in such objects have basic structural and aesthetic functions with a certain microstructure and appearance. However, fibers can also have added functions in the context of “wearable computing”, as previously recognized by Post and Orth.[3,8]

In terms of integrating computing power into clothes or other entities of that kind, we share the vision that “eventually, whole computers might be made from materials people are comfortable wearing”.[8] In a similar vein, Lind et al. stated, “it is only appropriate that the field of textiles takes the next evolutionary step towards integrating textiles and computers by designing and producing a weavable computer that is also wearable like any other textile”.[10] These ideas foresee the seamless integration/embedding of computational functions into textiles in a natural way without changing the original function of the entity. We believe that in order to make a computer “wearable”, one should dissociate the ordinary textile (clothing) into its basic components and seek a way of embedding or integrating the computing power into these components.

We propose the concept of fiber computing, in which the goal is to embed the basic unit of computation, the transistor, into fibers that make up the clothes we wear. These transistors then may be connected to form inverters, gates, and higher level circuits. In the context of fiber computing we define a fiber as material formed into a continuous geometry that has a very high aspect ratio and is a single piece. Our goal is to turn existing “bricks around the body” into a comfortable, flexible, washable, and wearable textile form. With the successful integration of these fibers into clothes, the infrastructure for making a computer truly weavable will be initiated.

Fibers can be made from almost any material (glass, ceramic, polymer, and metal), thus making them a versatile component in many industries. Fibers are often used either in yarn form for textile fabrics, in monofilament form (in medical and optical applications), or in multifilament form as reinforcement for composite materials. The properties of the material constituting the fiber ultimately determine its area of use. Polymer fibers are highly flexible, quite elastic and light, and are therefore best used in the textile-related industry. Metal fibers are heavier than polymer fibers, but they are electrically conductive, tough, and stronger than most polymer fibers, thus they can be used in self-supporting form or as reinforcements in other materials. Ceramic fibers are very strong and heat resistant and are mainly used in chopped or continuous form to reinforce materials, however, their brittleness and limited flexibility as well as high cost currently limit their applications to areas such as turbine, aerospace, and refractory technologies. Glass fibers are used in a range of different areas, from thermal insulation to optical telecommunications. In the latter, information is encoded in light and sent through an optical glass fiber that is thinner than human hair. The chemical composition and the microstructure of the glass fibers must be controlled carefully during manufacture, and although they are brittle, they are extremely strong.

In many cases, fibers are not just structural elements, but may also exhibit added functionality. In the textile sector, diverse functions are added to the fiber surface or directly into the fiber with the aim of improving a garment. The most interesting examples include the use of microencapsulation. Tiny capsules 1–10 μm in size are incorporated into the fibers or applied to the fiber surface using a resin binder. Examples of materials contained in the capsules include phase-change materials that change their physical state at pre-set temperatures by taking up heat from the surroundings[11] and color-change dyes that change color at a pre-set temperature (thermochromic dyes), or change color at a certain incident wavelength (photochromic dyes). Phase-change materials integrated into textiles may also assist in heat dissipation of wearable computers. Another possibility is the functionalization of the fiber surface with hydrophobicity/hydrophilicity, for example using plasma technology, in order to control behavior towards humidity. Furthermore, research is being performed to attach biopolymers to fiber surfaces or incorporate them into fibers to render them antimicrobial, wound healing, and so on. An added functionality may also refer to properties derived from the fiber cross-sectional geometry. In the textile industry this is used to control properties such as softness, luster, and drapability. For example, a round cross section results in brightness and a triangular one in sparkling effects.

2. Overview of Fiber Materials

Fibers may also exhibit inherited functionality based on the intrinsic material properties. Metal fibers, for instance, are conductive and can be used for transferring power or signals from one point to another.[1] Ceramics can be conductors (semiconductors, ionic conductors, superconductors), but may also be inherently functional as insulators.

To date, added and inherent functionalities have not been combined to yield fibers that can be described as having computational properties. The prerequisite to induce this property is semiconductivity, and while some commercial ceramic and polymer fibers already display this property, it is not exploited. SiC, for example, is a ceramic used in its single crystalline form for integrated circuit manufacturing where the ICs need to function at high temperatures and very high frequencies.[12–14] In the form of fibers, however, their use is restricted to mechanical reinforcements.[15–17] Thus the prerequisites for the computing fiber are given, and with all the technologies in existence today in the textile as well as in the materials manufacturing and electronics industry, it should be possible to produce thin, flexible, lightweight, and tough fibers suitable for integration of transistors.

3. Fiber Substrates for Semiconductor Industry

In order to develop integrated circuits on fiber substrates, we define three different classes of fiber substrates.

- Active: semiconductor material on which transistors are integrated.
- Passive: materials used as a carrier for the active material (this should not be confused with the term "passive components", which refers to circuit elements such as resistors and capacitors. When "passive components" are needed to form a circuit on the fiber, they will not necessarily be made out of "passive materials").
- Intermediate: this is the material that is used for special purposes such as modifying surface properties of an active or a passive material layer, or altering a specific property of an active or a passive material. It is used without being dissolved and retains its physical and chemical integrity, so it excludes alloying, doping, and so on. The model of active and passive fibers is shown schematically in Figure 1. Some candidate materials for each class are listed below.

3.1. Active

- Single and polycrystalline silicon. Examples of transistors exist in recent literature, especially for thin film displays.

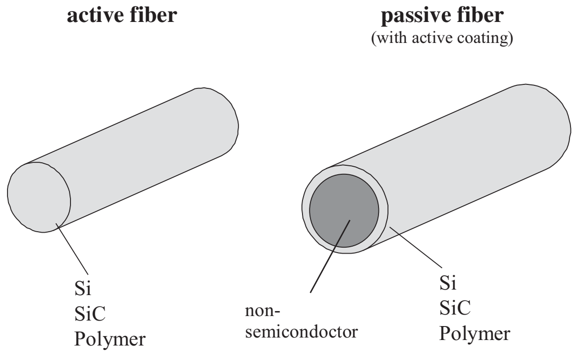

Fig. 1. Fiber classification: active and passive fiber model.

- Amorphous silicon is another possibility. Examples of transistors exist in recent literature, especially for thin film displays. It has a lower electron mobility compared to polycrystalline silicon.
- Semiconductor ceramic materials such as silicon carbide, which is already being used in high frequency microelectronic devices.
- Polymer integrated circuits can be found in literature. These "polytronics" exist, especially for thin film applications.

3.2. Passive

Passive materials could include polymers, glass or ceramics. These will be the materials that can be processed easily for their specific purpose (packaging or carrier fiber). In either case, the materials will be engineered if a need to alter a specific property arises.

3.3. Intermediate

An example of an intermediate could be a layer of amorphous SiO_2 that is used to modify the surface of a carrier fiber (passive) on which the active material is to be deposited.

4. Fiber Production for Semiconductor Industry

There are many different ways of producing fibers depending on the raw materials used as well as the final technology and applications they serve. Remembering the definition of a fiber in the context of fiber computing, we focus here on those processes that produce a continuous single piece of material in the shape of a fiber. Since the fiber has to be made from a semiconductor material, or one that will bear a semiconductor coating and the microelectronics fabrication process, the raw materials and the production process will be quite different from those targeted for the traditional textiles industry. In this context, the process will depend on the kind of the substrate material to be produced. Table 1 shows some techniques that can be used to produce fiber substrates.

Table 1. Fiber substrate processing technology for semiconductor industry.

Fiber material	Technology	Dimensions [μm]	Remarks
Si fiber	micro-pulling-down	> 120	insufficient flexibility
[18–23]	silicon-on-insulator	< 30	short fiber length
SiC fiber	extrusion	> 50	no single-crystalline structure
[15-17]	sol-gel	< 10	free carbon present
	precursor	< 10	free carbon present
polymer fiber	extrusion	< 10	size of the ICs too big for fiber
SiO_2 fiber	melt spinning	< 10	not pure silicon oxide
[24–28]	drawing	< 10	method for optical fiber
	extrusion	> 50	nanoparticles essential
	sol-gel	< 10	Si-precursors essential

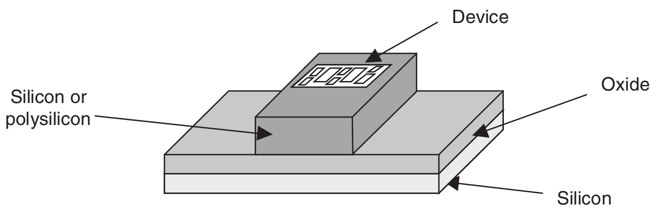

Fig. 2. Concept of SOI (silicon-on-insulator) fiber.

5. First Results

At the beginning of the Fiber Computing (FiCom) project, the partners focused on two different processes, namely SOI and extrusion, to develop new substrates in fiber form suitable for semiconductor processing.

5.1. SOI Fibers

After transistors are formed on special SOI substrates, they are extracted from the wafer substrate in the form of very long thin membranes by using etch techniques, which are well known in microsystems processing. Such so-called SOI fibers can be made using all standard planar processing techniques on the silicon overlayer (Figure 2). The buried oxide acts as an etch barrier to make the removal of the silicon from the back more manageable. The major advantage of this approach is that since the silicon overlayer is high purity single crystal silicon, it is possible to make any conventional circuit and extract it from the underlying silicon in fiber form.

SOI fibers have been successfully produced. A 1 μm thick polycrystalline silicon layer was deposited on oxide and removed from it using a dry etching technique. The handling of the fibers after lift-off was quite difficult because the fibers are quite long (up to 42 mm in length). Figure 3 shows an image of a SOI fiber after lift-off.

5.2. Fiber Extrusion

Extrusion is commonly used for the production of ceramic fibers. A mixture of fine ceramic powder and organic additives is compounded in a high shear mixer until the mixture, the so-called feedstock, is homogeneous. This feedstock is then pushed down a narrow barrel by a ram or screw and extruded through a small orifice. Subsequently the organic additives are removed from the fine extrudate, which is then sintered to obtain a ceramic fiber.

The organic components are necessary to provide good extrusion behavior, plasticity, and a sufficient strength after extrusion, but they must also be easily and totally removable by chemical and/or thermal means before sintering of the ceramic powder can take place. A big advantage of this process is that a variety of desired cross-sectional geometries and even hollow fibers can be realized.[29] With this process, first pure SiO_2 and SiC fibers have been successfully produced. Since boron and alkali species influence the semiconducting properties of silicon, borosilicate and alkali silicate glasses cannot be used to form the fibers being considered here. These atomic species diffuse readily at normal semiconductor processing temperatures (800–900 °C) and would make the integration of Si-based circuits onto such glass fibers impossible.

SiO_2 fibers sintered below 1200 °C exhibited an amorphous glass structure. Crystallization at the fiber surfaces was seen to occur at higher sintering temperatures. Some silica glass fibers were coated with a thin layer of silicon by using a PVD process. Figure 4a shows SEM pictures of such coated fibers. SiC fibers were sintered at temperatures above 2150 °C under argon atmosphere. After sintering the fibers exhibited a polycrystalline structure. Figure 4b shows a 150 μm SiC fiber after extrusion and after sintering.

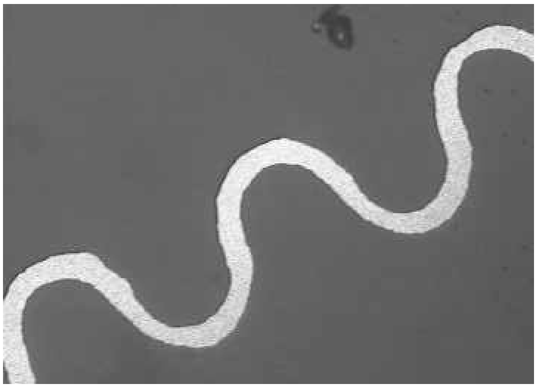

Fig. 3. Image of polysilicon fiber after lift-off, 1 μm thick polysilicon, 35 μm wide.

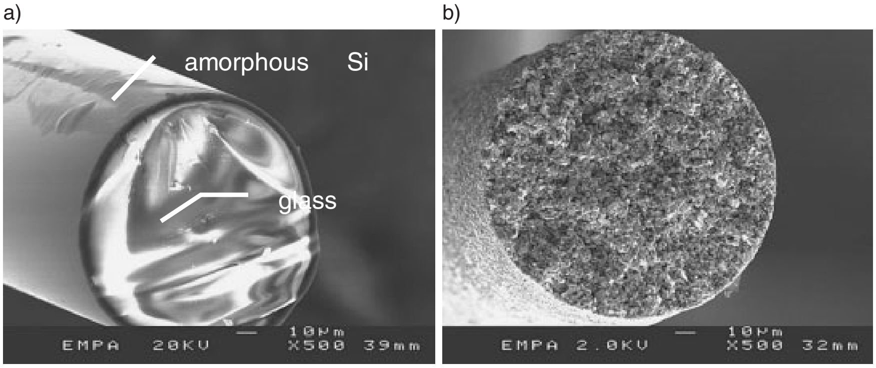

Fig. 4. a) Si-coated silicon oxide glass; b) sintered SiC fiber.

6. Integration into Textiles

Integration of computing fibers into textile materials requires consideration of the fiber package properties, commercial textile assembly methods and the properties that should be displayed by the final product. As shown in Figure 5, the integration procedure always starts with the individual fiber, which has been suitably packaged. Such fibers may be individually incorporated directly into the fabric, or may be assembled together with other textile fibers into a yarn to yield a tougher material. If the computing fibers are used in fabric structures, they must be resistant to the various degrees of twisting, which may be applied during yarn and fabric production.

The computing fibers or yarns can be processed by textile weaving or knitting techniques. In a plain woven fabric, the computing fibers are bent only slightly and therefore, the bending stresses are not as high as in some knitting variations where high deformations characterized by small bending radii may be possible. Plain knits are known for their high stretchability, and if the fiber is to be incorporated directly into a knitted textile, it should be able to sustain these high deformations. An alternative is to weave the computing fibers or yarns into a pre-knit structure. To be viable, computing fibers must thus tolerate deformation both during the production process and in everyday use.

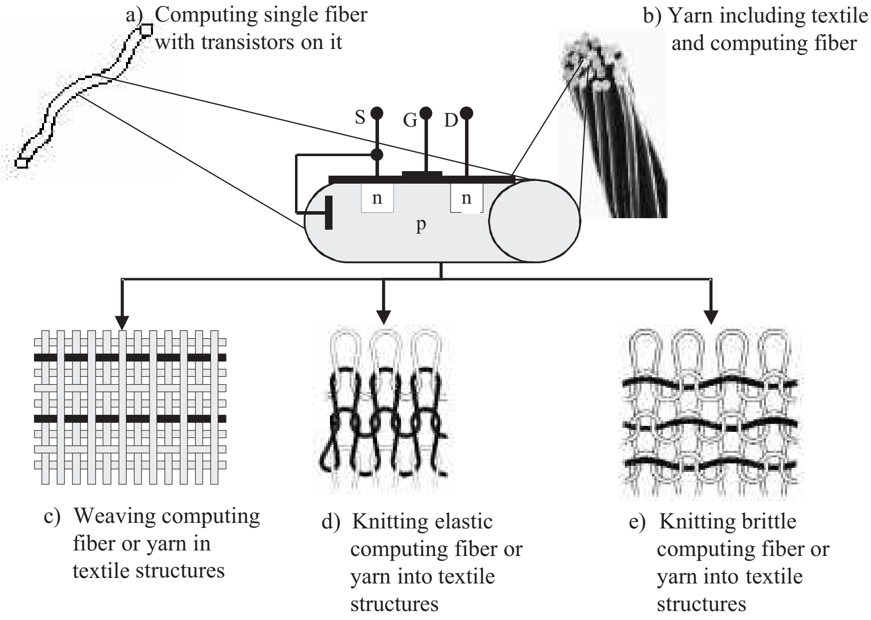

Fig. 5. Integration of computing fibers into woven and knitted textiles.

7. Conclusions

This Research News shows the pathway we propose to adopt to move from a wearable computer to a fiber computer, which is directly integrated into the garments we wear. This evolution would occur using computing functions embedded directly onto the fibers of the fabric. In a first step to realizing this concept, two different techniques have been used to develop substrates in fiber form, which are suitable for carrying semiconductor circuitry: Using the SOI process, polycrystalline silicon fibers with a length of 42 mm were successfully produced at NMRC in Ireland. The fibers were 35 μm wide and 1 μm thick and showed that dry etching techniques can be used to produce short fibers. Using a ceramic powder extrusion technique, endless fibers of SiC and SiO_2 were formed, cut to 20 cm lengths, and sintered to yield polycrystalline silicon carbide fibers and pure amorphous silicon dioxide glass fibers. Incorporating these fiber-shaped substrates into woven or knit structures constitute part of the future activities in this project.

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