# Fiber Computing

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## Abstract

*Fibers are materials that have a very long length compared to their cross sectional dimensions, i.e. a very high aspect ratio. A wide variety of everyday objects are either made out of or consist of textile fibers (clothes, wall paper, chairs). In this work, we describe a potential physical layer for wearable computing by using fibers. The layer is defined by the fabrication of transistors onto fibers, packaging and integrating these packaged fibers into textiles. These fibers need be made out of suitable semiconductor materials to host transistors. A piece of polysilicon produced into a very small cross section compared to its length is demonstrated. Due to space constraints on a single fiber, research into novel architectures is done to create parallel, distributed, fault-tolerant and configurable devices. Configurable fibers can be interwoven into clothes or everyday objects to create artifacts, which can be interconnected with each other.*

***Keywords***
*Wearable computers, fiber, transistor, textile, garment, electronics, ubiquitous, physical layer.*

## 1. Introduction.

Current state of the art in integrating electronics with ubiquitous or wearable systems involves starting with packaged integrated electronic components (ICs), interconnected with each other on a rigid or flexible [1] printed circuit board, the latter providing better conformity to the body. Enclosing these circuit boards for protection from environmental effects by a protective material or casing is a common process. Still, even state-of-the-art packaging techniques developed by product designers for wearable computing [2], fail to pass beyond "bricks" attached to the body. Some components on the other hand may have to stay as rigid structures that need to be integrated comfortably with the body [3]. In the case of ubiquitous computing, taking the media cup [4] as an example, a complete integration is not achieved since the electronics and the cup are two separate entities and the electronics need to be removed for washing the cup. There are also novel approaches towards integration of passive electronic components into objects, such as Post and Orth's [5]. They integrated conductive stainless steel fibers into textiles for the purpose of connecting circuit boards and point in the direction of a higher-scale integration. D. De Rossi et.al [6] used conductive polymers for sensing and actuation applications: A conventional fabric was coated with a thin layer of conducting polymer and conductivity changes on this coating as a function of strain and temperature were observed. A glove prototype made from this coated textile showed sensing and actuation capabilities embedded into a piece of textile. At the microscale, Drury et al. Reported all polymer microelectronic devices fabricated on flexible substrates at a low cost using organic semiconductors [7]. Given today's technology, it is possible to group the possibilities of integration of (micro)electronics into clothing at three levels [8]:

1. **Garment level integration:** At this level, the fundamental design of clothing and electronics are

accomplished independent from each other and are combined at a later stage. A good example of this type of integration is the Philips-Levi's ICD jacket [9].

2. **Fabric level integration:** The electronics is integrated into the fabric that the garment is made out of. A good example of this level is circuit boards attached onto the fabric connected to each other using conductive threads. Integration of electronic components, such as sensors and integrated circuits [10] are also examples that can be included in this group. This provides a relatively unobtrusive way of integrating electronic components into clothing.
3. **Fiber level integration:** Part or all the necessary electronics and sensors are directly integrated into the fibers that make up the yarns.

Today, examples that are based on the use of fibers for electronics are not plenty except for examples like conductive threads/yarns [5] and sensors [6] and it is possible to state that the opportunities at this level are not thoroughly explored yet. In this work we focus on the possibilities of microelectronics-textile integration on the fiber level. "Fiber" is generically defining the geometry of a material having very long length compared to its cross sectional dimensions, i.e. a very high aspect ratio. Human hair is a good example for visualization of fiber geometry. Fibers are used in many different areas of industry, from textiles to optics to advanced composite materials. In ordinary daily life, a human interacts with many objects that are either made out of fibers or contain fibers in their structure. Simplest example is naturally the textile in the form of clothes, curtains, table clothes or textiles of that sort. Interactions with more advanced uses of fiber such as telecommunications are indirect and not in the form of a physical interaction with human. Today, fibers in the aforementioned everyday objects have basically structural and aesthetic functions with a certain macrostructure and appearance. However, "fibers" can also have added functions in the context of "wearable computing" as previously recognized by Post and Orth [5, 10]. In terms of the integration of computing power into clothes or entities of that kind, we share the vision that "eventually, whole computers might be made from materials people are comfortable wearing" [11]. 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 textiles" [12]. These ideas foresee the seamless integration/embedding of computation 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 (e.g. clothing) into its basic components and seek a way of embedding or integrating the computing power into these units.

We propose the concept of "Fiber Computing" in such an effort where 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 "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 and washable wearable textile form. With the successful integration of these fibers into clothes, the infrastructure for making a computer "truly weavable" will be initiated.

## 2. State of the Art in Fiber Materials.

Fibers can be made from almost any material (glass, ceramic, polymer and metal) thus making them a versatile component for many industries. Fibers are either used by themselves in interwoven form (e.g. textile industry) or in single form (e.g. medical field) or as reinforcement for other materials (e.g. composite materials industry). The property of the material that the fiber is made of ultimately determines 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. They are used by themselves as wires or to reinforce other materials such as ceramics, thus forming composites. Ceramic fibers are very strong and are used in chopped or continuos form to reinforce materials (again composites). However, their brittleness and restricted flexibility as well as high costs currently limit their applications to rather exotic areas like aerospace technology. They are also used in heat insulation for high temperature applications. Glass fibers are used in different areas, from heat insulation to telecommunications. In the latter, information is encoded in light and sent down 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 manufacturing. Although they are brittle, they are extremely strong.

In many cases, fibers are not just structural elements but may also display added or inherited functionality. In the textile sector, diverse functions are *added* to the fiber surface or directly into the fiber with the aim of an improved garment. The most interesting examples include the use of microencapsulation. Tiny capsules, of 1-10 µm in size are incorporated into the fibers or applied to the fiber surface using a resin binder. Examples of materials included into the capsules include phase change materials (change their physical state at pre-set temperatures by taking up heat from the surrounding) [13] and color change dyes (change color at a pre-set temperature = thermochromic; or change color at a certain incident wavelength = photochromic). Phase change materials integrated into textiles, may also assist in heat dissipation of wearable computers. Other added functionality includes the functionalization of the fiber surface (possibly with plasma technology) with hydrophobicity / hydrophilicity in order to predetermine behavior towards humidity. Furthermore, research is being done to attach biopolymers to fibers or into fibers to render them antimicrobial, wound healing etc. An added functionality may also refer to a functionality that is 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.

*Inherited* functionality is based on the intrinsic material properties. The simplest examples are metal fibers: because they are metals, they are conductive and can be used for transferring power or signals from one point to another. Ceramic fibers are by far the group with the most versatile inherited properties. They can be insulators or semiconductors. Among others, fibers were made from $Si_3N_4$, SiC, $Al_2O_3$, PSZ (partially stabilized zirconia), PZT (lead zirconate titanite) [14] PMN (lead magnesium niobate) and YFe (yttrium ferrite) [15]. PZT, for example, is piezoelectric and can produce an electrical potential when exposed to mechanical strain or visa versa. PMN is electrostrictive (exhibiting non-linear conversion between electric field and mechanical strain) and YFe is ferrimagnetic (fiber exhibits a macroscopic magnetic moment). All these fibers find different uses in specific applications. Many ceramic fibers are also produced as hollow fibers for use in filtration and water treatment.

In some cases, *inherited* and *added* functionality can be given by one material. For example, ceramic $TiO_2$ particles are added during the polymer fiber production process to enhance the fiber properties due to their *inherited* material properties: (*i*) absorb dangerous UV radiation and (*ii*) give a white color. At the same time, this is an externally *added* function to the original fiber. Figure 1 shows the properties the fibers can achieve inherently or by the addition of another material.

Most kind of fibers are produced by extrusion, spinning or centrifuging. Extrusion has the advantage that almost any kind of cross-sectional shapes can be produced in-situ. Furthermore, different materials can be co-extruded into one fiber.

No fibers thus far existing can be described as having computational properties. The prerequisite to induce this property is semiconductivity, which some commercial ceramic and polymer fibers already display. SiC for example is a ceramic and used in its single crystalline form for integrated circuit manufacturing where the ICs are to perform at high temperatures and very high frequencies. In the form of fibers, however, their use is restricted to mechanical reinforcements. With all the technologies existing today in the textiles as well as in the materials manufacturing and electronics industry, it is possible to produce thin, flexible, light weight and tough fibers suitable for integration of transistors.

## 3. Issues for Integration of Microelectronics and Fibers

Many questions need to be answered before the concept of "fiber computing" can be brought to embodiment as this is a concept unparallel to the conventional methods of microelectronics and textile industry. We group the challenges as follows and will outline each briefly:

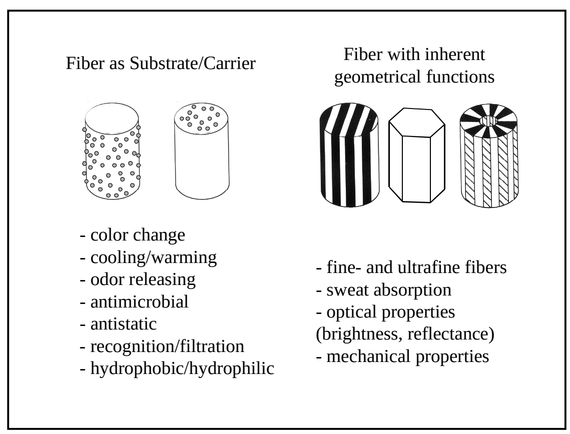


**Figure 1. Properties that fibers may display depending upon their usage as substrate/carrier or their inherent geometrical functions.**

1. Material selection
2. Fabrication issues
3. Packaging

4. Integration into textiles
5. Reliability and scalability

## 3.1. Material Selection

Fibers need to be made out of suitable materials that will host the transistors and be flexible. Although flexible electronics is now evolving such as polymer electronics [7, 16] as well as flexible AMLCDs [17], the magnitude and frequency stresses that our clothings suffer may be harsher especially during maintenance (such as washing). Packaging will certainly play a crucial role in minimizing the stresses that the core fiber carrying the electronics will experience. The traditional material of the semiconductor industry, silicon, may prove to be not the best material in its single crystalline form in terms of mechanical properties. It is therefore envisaged that a composite fiber structure will be most suitable in terms of mechanical properties (not including packaging since it is necessary in any case). The composite structure may consist of passive and active parts made out of different materials, the former with adequate electrical (e.g. insulator) and mechanical (e.g. compliant) properties. The active part will then host the transistors and hence needs to be a semiconductor material, which may be of different types (metal, ceramic or polymer - polycrystalline, single crystalline or amorphous) and in different forms (as bulk or thin films). Active and passive parts may be combined in different ways to form a fiber that incorporates transistors.

## 3.2. Fabrication Issues

As far as fabrication is concerned, the substrate will be defined in 2D cylindrical coordinates ($\theta$ and $z$) rather than 2D cartesian as in the conventional silicon technology. Transistor fabrication on curved surfaces however is not entirely new and several examples already exist. [18, 19] The basic question will be the handling of fibers during fabrication and interconnections between the transistors. Currently, we are focusing on proof of concept by demonstrating prototypes using different materials and fabrication methods.

## 3.3. Packaging and Reliability

Packaging is one of the critical engineering steps as it is ment to protect the fiber and its circuits electrically, optically, and mechanically as well as giving textile characteristics to the fiber. Mechanically the flexibility and the mechanical stress exerted on the fiber will depend on the geometry and the material properties of the packaging material. Optically, the packaging material should be opaque to prevent photon excitation in the semiconductor, and it should be an insulator for electrical protection. However static charge build-up on the packaged fiber should also be avoided. It is also the step where the connections to the outer world, I/O and power are defined.

Reliability refers to an estimate for the ability of a system to function properly over time [20]. The main concern about the fibers with transistors are defects that may occur during integration to textiles (see section 3.4) and during the use of these garments. The failures during the latter may occur from mechanical, electrical or chemical forces. Packaging and reliability are closely related since the former is critical for protection against these effects. It should however be kept in mind that the same forces act on the I/O and power connections and it is of equal importance to protect them also. Mechanical forces may cause interfacial decohesion, rupture or fracture of these fibers. Electrically induced failures include electrostatic discharge in the packaged fiber, electrical overstress and latchup. Chemically induced failures include contamination. These failures can also be induced dependent on time due to mechanical creep, eletromigration, or chemical diffusion/corrosion. As these fibers will be exposed to maintenance of the garments they are on (e.g. washing), time dependent effects will be more significant. Therefore packaging should be well engineered to protect the fibers while maintaining necessary mechanical properties.

## 3.4. Integration into textiles

Integration of the computing fibers into, e.g. the textile material needs considerations related to fiber packaging, commercial textile assembly methods as well as the properties that should be displayed by the final product. As given in Figure 2 the integration procedure always starts with the individual fiber (Fig. 2(a)) which has been packaged adequately. This fiber may be assembled together with other fibers into a yarn (Fig. 2(b)). These other fibers are fibers that the bulk textile material is made from. This incorporation provides an additional protection to the computing fiber. However, the computing fiber must be resistant to the various degrees of twisting which may be applied during yarn making. If this step is not necessary or impossible, the single computing fiber may also be incorporated directly into the textile during fabrication. Here, the most relevant way of incorporation depends upon the stress/strain level that the fiber can sustain. For example, in a plain weave the fiber experiences deformations characterized by very small angles (Fig. 2(c)), whereas in some knitting variations, high deformations characterized by a high angle of bending may be possible. If the fiber is to be incorporated into a knitted textile that needs to be very elastic, it should be able to sustain these high deformations (Fig. 2(d)). Plain knits are known for their high stretchability. Should that property needs to be retained, computing fibers must comply with the production process as well as the rougher conditions experienced during handling.

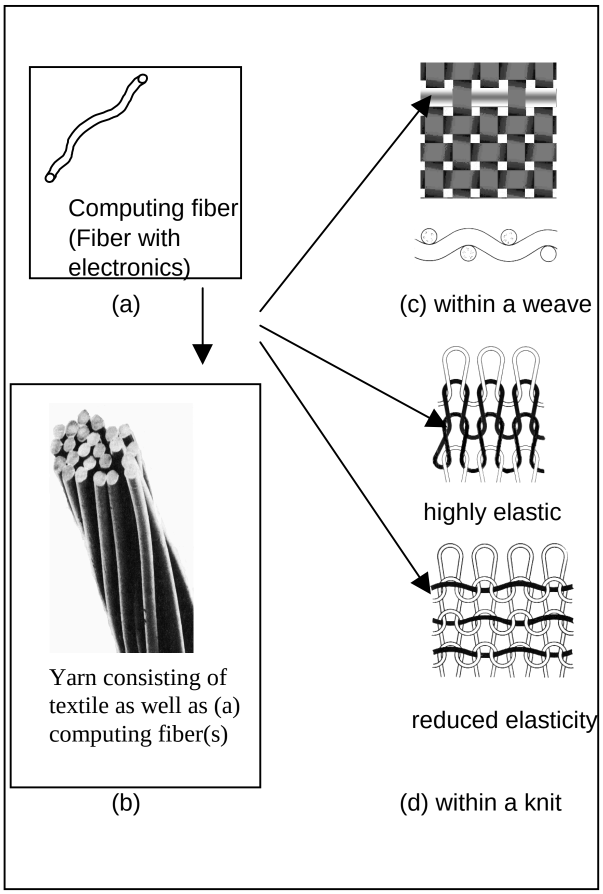


**Figure 2. Hierarchical issues to be considered for the integration of computing fibers into textiles.**

### 3.5. Scalability

We believe that we can scale the number of transistors starting with a single transistor to many transistors using the surface area of a fiber. Main concern is the interconnections since fiber is practically one dimensional. Therefore the feature size becomes an important parameter which will determine the number of transistor across the perimeter of the fiber. Clock and power distribution are also important since transistor to transistor distances might get quite large.

## 4. Fiber Production

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 are focusing 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 method will depend on the kind of material to be produced. For the production of a ceramic fiber, extrusion is one of the common processes where a mixture of fine ceramic powder and organic chemicals is pushed through an orifice and sintered to obtain a ceramic fiber. One can realize a variety of desired cross section geometries or even a hollow fiber using this method. Figure 3 shows a sintered hollow lanthanum strontium manganate ceramic fiber produced by extrusion that has ~120μm outer diameter and ~30μm wall thickness. Materials are able to exhibit different mechanical properties in the fiber form than in the bulk form. For example a ceramic material, although the brittle nature of the material is preserved, can exhibit higher elastic deformations due to the very high aspect ratio of fiber geometry. The same is true for single crystal silicon, where ~20 μm thick wafer will deform considerably (almost like a piece of high quality paper) and a standard wafer of ~500 μm thick will break before showing visible deformation to the naked eye.

Other methods such as sol-gel processes for ceramic fiber production also exist. In case of metals, the most common method is fiber drawing where the metal is pulled (as compared to pushing in extrusion) through the orifice at a temperature dependent on the kind of metal. In case of glass, fibers are pulled through an orifice at high temperature similar to metals although the two processes differ considerably in details. In most cases, the materials are post processed for various reasons such as elimination of residual stresses. In case of silicon, fiber drawing is not a common method due to its mechanical properties. We were able to produce polysilicon pieces with fiber geometries using traditional lithography and etching methods. Figure 4 shows a part

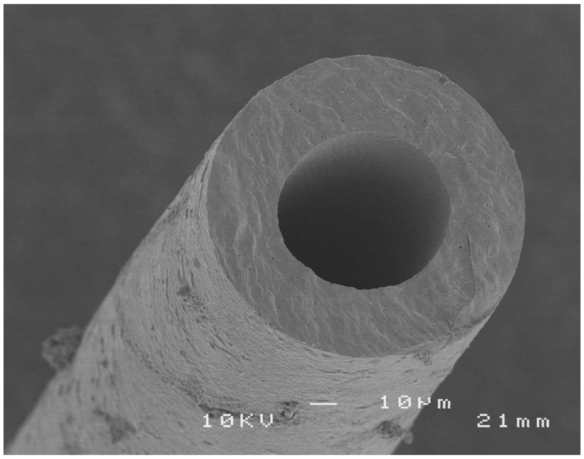


**Figure 3. Cross section of a sintered hollow ceramic fiber produced by extrusion [14].**

of such a polycrystalline silicon 'fiber' with a cross section of ~35x1 $\mu m^2$ and length of 40 mm. The method offers versatility in shape and makes it possible to process also single crystalline silicon into fiber form [21]. The biggest advantage offered by this method is the use of traditional microelectronic fabrication techniques for silicon with minor corrections

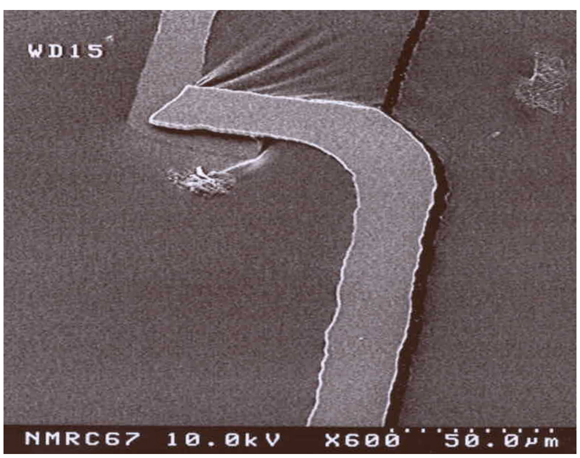


**Figure 4. Part of a polycrystalline silicon of 35x1 μm cross-section with a length of 40mm produced by optical lithography and etching.**

in layout while other processes such as doping, oxidation and deposition remain the same.

## 5. Computer Architecture Issues

In today's technology, digital logic elements, such as AND gates, are often realized through complementary metal oxide semiconductor (CMOS) technology [22]. The heart of digital logic is the inverter, which combines NMOS (n-channel Metal Oxide Semiconductor) and PMOS type (p-channel Metal Oxide Semiconductor) MOSFETs (Metal Oxide Semiconductor Field Effect Transistor). It is possible to interconnect inverters to form logic gates, modules (i.e., arithmetic logic unit) and systems (i.e., central processing unit). However, the interconnection requirement between these subsystems (starting at the inverter level) make the whole system vulnerable to defects in the manufacturing as well as defects that may be introduced during use. Another limiting factor is the surface area of fibers, which limits the number of transistors that can be implemented for a given feature size. The number of transistors will determine the complexity of the circuits that could be implemented in fiber form.

Due to constraints described above, fault-tolerant and distributed architectures are needed for fiber computing. An example of distributed, parallel, scalable, reconfigurable and fault-tolerant architecture that is also a turing machine is 'cell matrix' [23]. Cell matrix is made up of identical hardware where the smallest unit of processing element is the 'cell' consisting of a special shift register, 4 to 16 selector, D flip-flop and couple of logic gates. With a collection of cells it is possible to build interesting circuits with various properties, resulting from the flexibility at a single cell level. At the single cell level, each cell has a duality in property; being the one to configure the neighboring cell or be configured by the neighbor. Each cell contains a truth table mapping the inputs to the outputs. By changing the truth table content (software), it is possible for changing functionality, this is how the cell matrix becomes reconfigurable. Given many cells, if some cells are terminated for some reason, the system will still be robust since there is no special hardware that is mission critical to system operation.

In a digital clothing application, at the higher level, one can imagine applications where sensors or the processing done on the sensors are not fixed at specific locations but they need to change over time. Cell matrix or a cell matrix like architecture can facilitate the implementation of wiring between sensors, logic elements, as well as processing of sensor data for presentation or decision making.

## 6. Conclusions and Ongoing Work

We propose a new approach towards the realization of a truly wearable computer by fabricating transistors on fibers that are to be included in textiles. Milestones towards the realization of this vision were discussed together with possible issues at different steps. As an initial example, a polycrystalline silicon of 40mm long and 35x1 $\mu m^2$ was fabricated using conventional lithography and etching methods. Work is going on in areas of alternative materials selection and layout partitioning for fiber geometry as well as packaging. A fault tolerant and reconfigurable computer architecture is being researched to be implemented for the 'computing fibers'.

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