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ELECTROTEXTILES: CONCEPTS AND CHALLENGES

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Electrotextiles (e-textiles) are fabrics made from yarns that carry electronic components. Circuits are made from such yarns by weaving. We describe the technical development of the concept of e-textiles, and briefly discuss three challenges: connectivity, materials and fabrication, and wear.

Keywords: Electrotextile; wearable electronics; woven circuits.

1 The Concept of Electrotextiles

The concept of electrotextiles, or e-textiles, has evolved from the concept of wearable computers. Wearable electronics have been demonstrated in the US[1,2] and in Europe.[3,4] Clothing companies have started to market products that carry hybrid mounted electronics,[5] and the U.S. Armed Forces have conducted programs to develop uniforms that incorporate electronics.[6]

Wearable electronics and electronic textiles lie at the two ends of a spectrum that ranges from added-on electronics to components integrated with textile yarn to true integration as shown in Fig. 1.

A first-generation wearable computer enables an engineer to compare blueprints with a workpiece in real time, as illustrated by Fig. 2 from the Carnegie Mellon program.[1] The application is clearly defined, and while the system is wearable, it is not integrated into the clothing of the user.

In the second generation of wearable computing, the system is surface mounted on clothing in a hybrid package. This approach is illustrated by Fig. 3, taken from

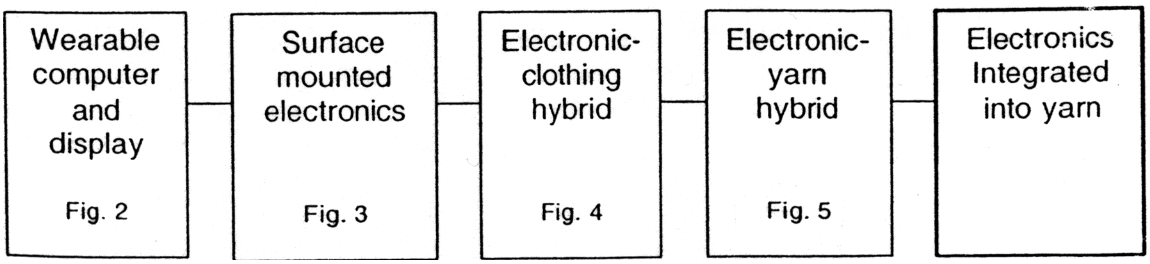

Fig. 1. A continuous spectrum of integration of electronics into textiles exists between wearable computers on the left and electronic components integrated into yarn on the right.

Fig. 2. Wearable electronics are body mounted but not integrated. This kind of wearable computer represents the first generation of practical, body-worn electronics.[1]

the MIT MediaLab's Mithril project,[2] and this is the concept adopted today by leisure fashion companies.[5] The system components are distributed over a vest that has a secondary function as clothing, in the same way that a tool belt functions as a clothing belt. This approach is prominent at the IEEE Symposia on Wearable Computers.[7]

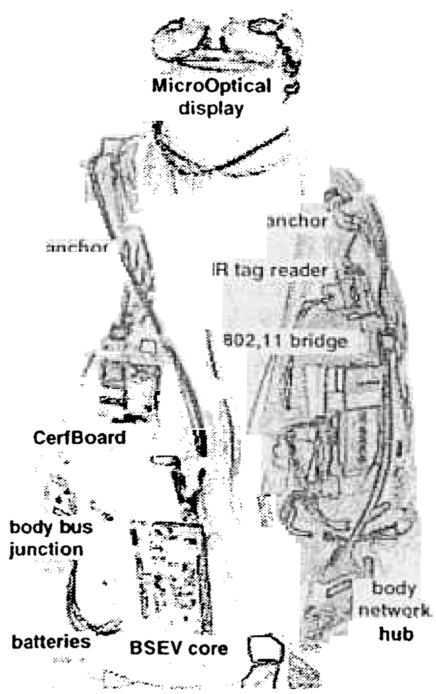

Fig. 3. Surface mounted electronics are the next step toward integrated e-textiles.[2] Surface mounting is entering commercial leisure products.

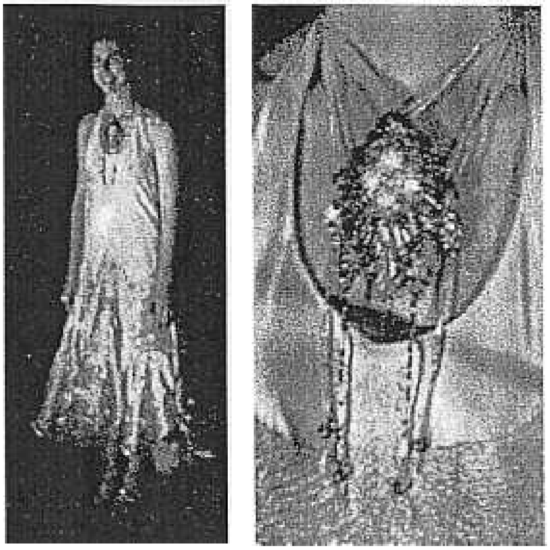

Fig. 4. A measure of integration is achieved with lighting attached to dresses and in jewelry. Here electronics serves to enhance the appeal of clothing, instead of just using it as a carrier.[8]

In the third generation of wearable electronics the electronic and the clothing functions are equally important, as illustrated by the two demonstrations from the MIT MediaLab and International Fashion Machines shown in Fig. 4.[8] Both the dress and the necklace meet clothing and esthetic functions and they carry lighting and sensing functions. This third generation is an important step toward true electronic textiles.

From this point on the concept of wearable electronics blends into that of electronic textiles. A case in point are early efforts to add an electronic function to e-textile yarn, as illustrated by Fig. 5, which shows a fabric made of plain silk thread warp and a weft of silk thread wrapped with copper foil.[9] This is an important conceptual advance in that the integration is brought to below-device level, but it still is a hybrid. It combines the separate free-standing functions of textile yarn and copper conductor.

Nearly all of these initiatives approach electrotextiles from the systems level. They attempt to answer the question how known, or desirable, electronic functions

Fig. 5. The weft yarn of this fabric is silk wound with copper foil. This is an example of hybrid electronics at the yarn level.[9]

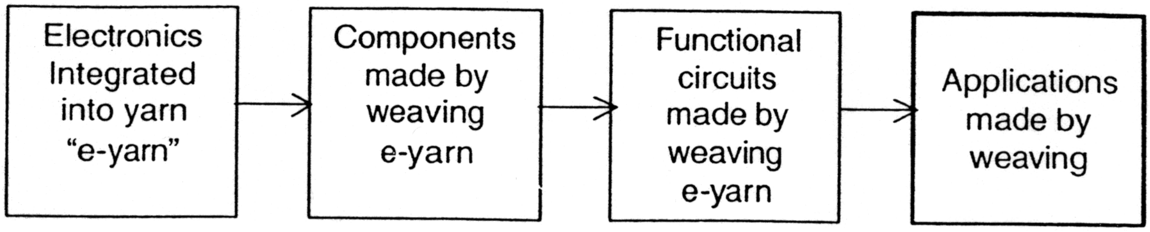

Fig. 6. Integration from the yarn level (rightmost frame of Fig. 1 and leftmost frame above) to components and functional circuits made by weaving the yarns, and eventually to applications such as smart actuating textiles.

can be worn on the body in comfort. This applications oriented approach indeed is needed to target early product opportunities, and the current pressing need for pervasive security may give birth to the first generation of clothing integrated sensor electronics. However, the hybrid approach responds to the task of marrying electronics and textile technologies at a superficial level, quite literally. Electronic patches are applied on fabric or are inserted into pockets. Stand-alone components that would function by themselves — clothes, DVD players — are combined.

E-textiles represent integration at the yarn level. E-yarns are used to make functional circuits, and are made functional by weaving. This approach is illustrated in Fig. 6, which in a sense is the inverse of Fig. 1. E-textiles take the approach taken by the I.C. industry, which first developed component technology and then proceeded to ever higher integration.

Wearable electronics follow the microprocessor model. Their components are miniaturized and are applied in high functional density. E-textiles follow the flat panel display model. They are large-area electronics with low functional density. Because early e-textiles are expected to be built of low performance components, it is likely that e-textiles will be hybridized with silicon integrated circuits.

2. Technical Challenges

We select three challenges for discussion: connectivity, materials and fabrication and wear.

2.1 *Connectivity*

A large range of techniques exist for making fabric from yarn.[10] These techniques represent a variety of possible ways for making electric interconnects. The circuit engineer seeks to make permanent interconnects to ensure high manufacturing yield and operational reliability.

A simple example for taking advantage of the connectivity of woven fabric is illustrated by Fig. 7, which shows schematically how solar cells made on different yarns may be connected in series by weaving. The colored and black segments are solar cells and the gray areas are insulating portions of the fibers. In Group A, fiber segments are electrically connected on both sides, except for an insulator between

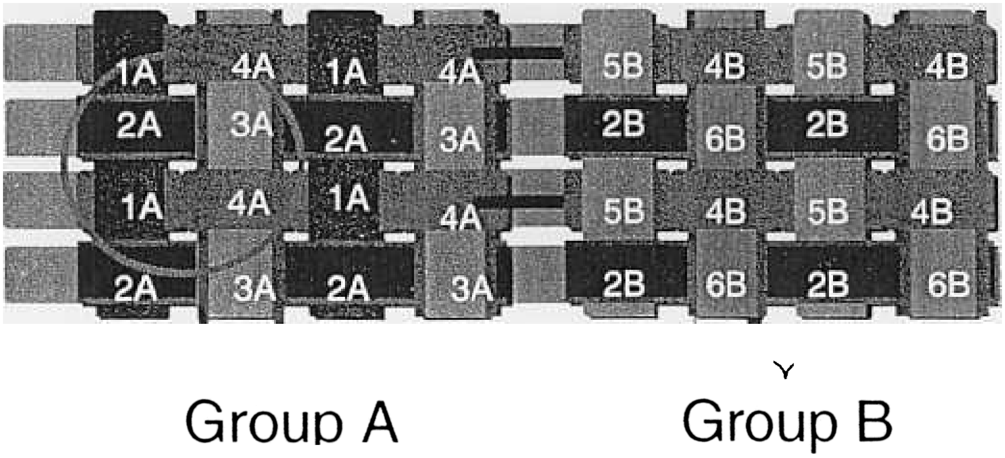

Fig. 7. Series connection of solar cells by weaving. Groups A and B are separate circuits.

1A and 4A. Thus fiber segments 1A through 4A are in series in numerical order. Therefore, the voltages add, and the fibers/geometries must be engineered such that the photocurrent in each fiber segment is the same. To connect Groups A and B in series, the top contact of 4A is connected to the bottom contact of 4B, as shown. Note that all fibers may require patterning since the series combinations must be horizontal-vertical-horizontal-vertical-etc. to adjust to the orthogonal nature of the weave. To connect the groups in parallel, the bottom of fiber segment 1A must be connected to the bottom of segment 5B (which would add much complexity to the weave), while the top of 4A would be conveniently connected to the top of 4B. Several groups could be connected in series to achieve a desired voltage, and then several of these series groups could be connected in parallel to achieve a desired current. To reduce possible shading effects, care should be taken to combine as few groups (or as small an area) as possible in series, and then to connect the parallel groups with diodes.

When fabric is draped the yarns experience shear. As the number of fixed interconnects is increased, the fabric stiffens and its drapability is diminished. This is illustrated by Fig. 8. To preserve drapability one can design the fabric such that it is connected only at its edges, as illustrated by the left panel of Fig. 8. Doing that requires the design and fabrication of yarn that allows addressing a large number of cells placed on the yearn with a small number of wires. One example of a cell design for fiber is shown in Fig. 9. This cell contains a (pressure or light) sensor. It is addressed by sequential sampling. Each cell contains only 17 transistors, and the fiber needs to carry only 6 wires.

This circuit can be used to sequentially sample each cell in the line. The circuit of every cell is identical. An arbitrary number of cells can be in each string, but the driver circuit will have to be configured to accommodate the exact number of cells. The D flip flops pass the input at D to the output at Q when the clock input C receives a high signal from the clock. Therefore, with this Master (D_M)–Slave (D_S) configuration, the address pulse will propagate from D_M to Q_M/D_S when C_M is

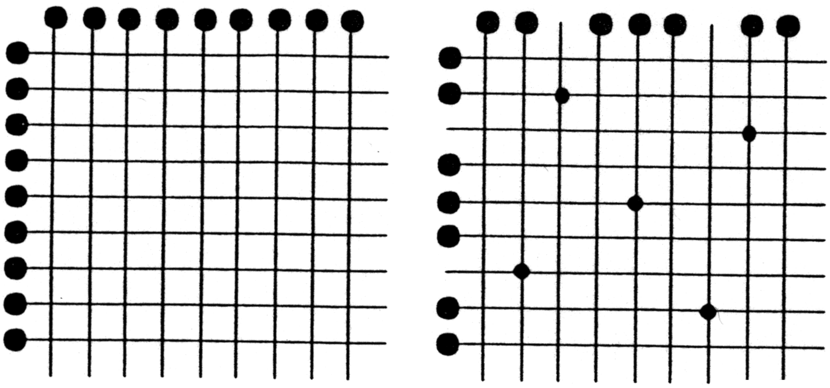

Fig. 8. As the connectivity of a fabric is increased, it becomes stiff and its drapability is reduced.

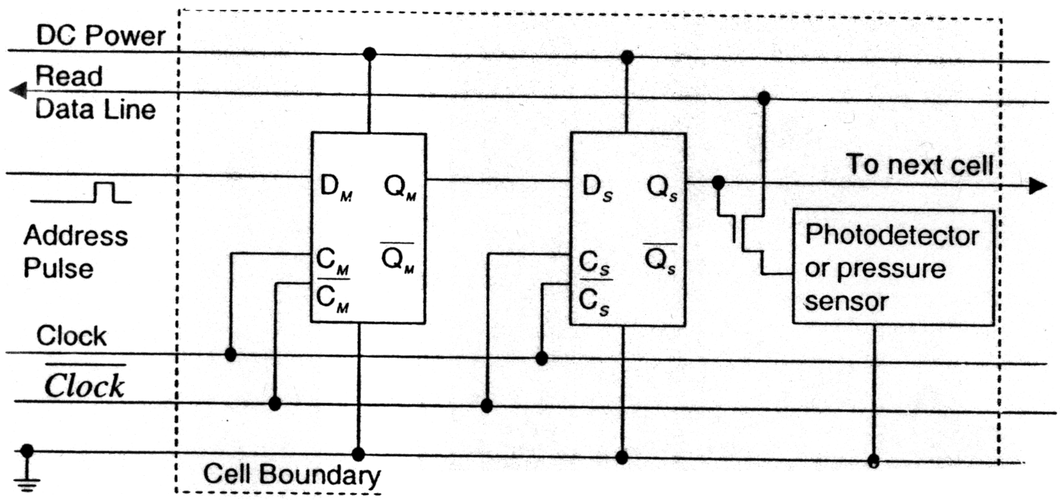

Fig. 9. Cell of an on-yarn circuit used for sequential sampling of sensors mounted on the yarn. Each D flip flop contains 8, plus 1 pass transistor = 17 per cell.

high, but cannot pass to Q_S since C_S is low. During the second half of each clock cycle, D_M cannot pass the signal since C_M is low, but D_S will pass the signal to Q_S (and D_M of next cell) since C_S is high, and so on. When the address pulse appears at Q_S, the transistor is turned on, passing the data to the data line to be read by the read circuit on the driver chip. The address pulse will propagate on down the line, moving from one cell to the next with each clock cycle, causing data from each successive cell to be sent to the read circuit for every low portion the clock period.

We expect that designing small wire and component count cells will be an important task in the development of e-textiles. This need is similar to the need for low-transistor count intelligent pixels, which also is on the research agenda for ASICs, such as on-pixel processing for CMOS based camera sensors.[11]

2.2. *Materials and fabrication*

Silicon based thin film transistors can now be fabricated at temperatures as low as 150°C, and can be made on foils of glass, steel, and of certain organic polymers.[12] While all of these materials can be made into yarn, and might be employed in

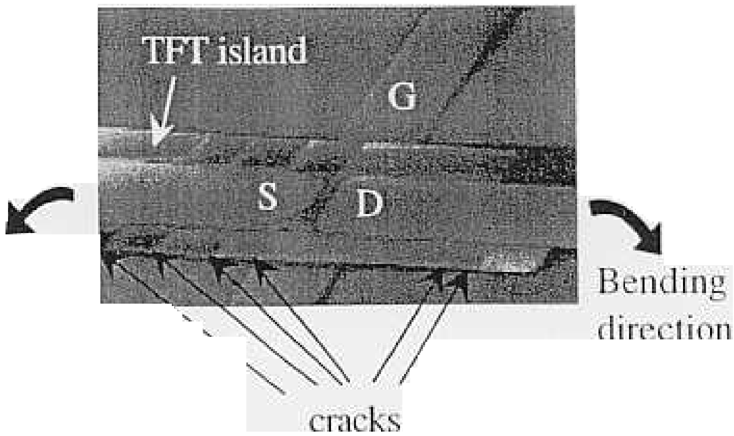

Fig. 10. Scanning electron micrograph of an a-Si:H thin film transistor that failed electrically by mechanical fracture of a SiN_x layer.[13]

specialty fabric, the most attractive yarn materials are organic polymers. The temperature of 150°C separates high-temperature polymers from the large volume polymers used for consumer applications. Therefore one target of e-yarn fabrication is to reduce the fabrication temperature. Several groups of semiconductors are available, including silicon processed at ultralow temperatures, II–VI compound semiconductors processed by wet chemical and electrochemical techniques, and organic semiconductors. None of these semiconductor materials has reached maturity in low temperature processing. While present attention is focused on obtaining these various semiconductors with good device properties, future concerns common to each will be stable dielectrics and ohmic contacts.

2.3 *Wear*

Bending

When used in e-textile, an e-yarn will be subjected to bending, stretching and shear. The consequences of bending on the performance of a-Si:H based thin film transistors have been studied in some detail. A-Si:H TFTs become less susceptible to bending to a given radius when the substrate is made thinner. While bending affects the electrical performance, the TFTs fail by mechanical fracture of one of their component layers, as is evident from Fig. 10.[13] It also appears that long-time fatigue may cause failure at lower strains than needed to fracture a TFT initially.

Stretching

Yarn may be stretched during wear. The transistor material will tolerate tensile strain up to relatively small values. The technique developed to protect the semiconductor circuits from mechanical failure is illustrated in Fig. 11. The circuits are placed on hard islands, here a-Si:H on SiN_x, such that the strain developed in the stretched fiber is concentrated between the islands.[14] Design rules for island size and thickness, and for interisland spacing, have been developed.

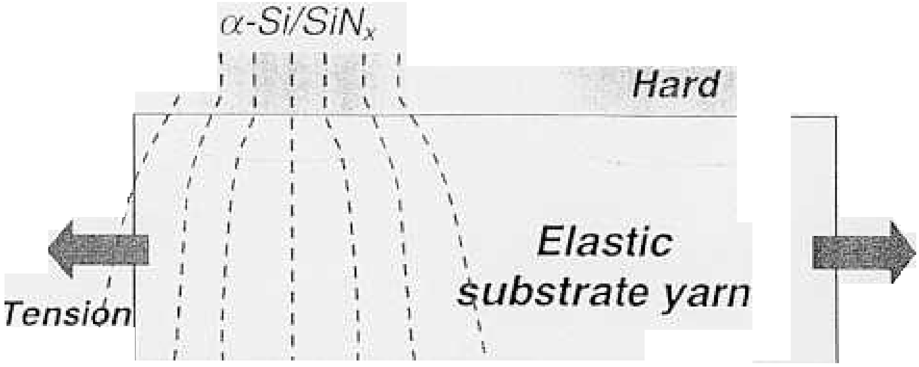

Fig. 11. Concept of hard device islands on elastic substrate. Design rules have been developed for sizing the islands such that their strain remains below a critical value while the yarn is stretched.

No standard approach to making stretchable interconnects exists at present.

2.3.3 *Shear*

Shearing yarns against each other during draping has two consequences. One is the making and unmaking of nonfixed electrical interconnects. The ensuing need for reconfiguring the local circuit from newly interconnected components will depend on some neural net capability of the e-textile. The second consequence is abrasive wear associated with shear friction. This is another aspect of e-textile that needs to be understood and prevented.

Acknowledgments

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