Investigating the Architecture of Flexible Large-Area Hybrid Systems

Combining thin-film sensor electronics with CMOS creates a new technology that marries the advantages of flexible large-area electronics with the speed and processing power of nanoscale ICs. Several features of this new architecture could benefit the development of comfortable, wearable electronics.

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TODAY'S WEARABLES are designed to connect the consumer with the Internet, observe bodily functions during physical exercise, watch the health of medical patients, or monitor the stress signals of emergency professionals. Wearables may be worn on the wrist, as armbands, or in pouches. Today, most wearable devices are discrete and usually visible.

Experiments and demonstrations of electronic textiles have revealed that customers like the idea of electronic clothing – clothing that incorporates wearable devices – but want it to be as comfortable and lightweight as everyday clothing. Most people are highly sensitive to the property of a fabric that is called "hand;" is it soft, flexible, and smooth or hard, stiff, and rough? Furthermore, wearers want the electronic machinery to invisibly merge with common articles of everyday use.

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In meeting these challenges – developing wearable electronics that seamlessly integrate into everyday clothing – much can be learned by considering recent materials innovation in the area of synthetic fabrics. With industrial scaling and corresponding price reductions, novel synthetic fabrics are being incorporated into a wide range of products. In particular, fierce competition in the clothing industry has led companies to rapidly license and adopt new synthetic fabrics, thus adding value to their product offerings and achieving higher margins. For example, Lululemon, a maker of athletic wear, has licensed a proprietary antimicrobial material from Noble Biomaterials for anti-odor clothing, Nike has Dri-Fit fabrics with moisture-wicking properties, and the Swiss Barefoot Company offers Kevlar socks as an alternative to traditional shoes.

We believe that for the first generation of wearable electronics, these types of fabrics will act as the scaffolding, which will provide a physical structure for clothing with embedded discrete sensors and output devices. Driven by the need for reliability, low cost, and rapid entry to market, the makers of these initial wearables will not focus on developing new electronic components with a flexible form factor. Rather, they will exploit the vast library of existing components typically found in consumer embedded electronics. In order to mitigate the undesirable rigidity of electronic components, they will attempt to minimize their density and conceal them through strategic placement (Fig. 1).

Electronic Fibers

The question remains whether the first generation of wearables will use electronic components with wireless connections or whether hardwired interconnects should be favored due to their reduced cost, complexity, and lower power consumption. Developers have already accumulated a great deal of experience integrating conductor wires into conventional yarn during spinning. In fact, many interconnects and resistors have been spun into yarn. However, together with their packaging, these materials are considerably more rigid than textile fiber. Such textiles become even more rigid when yarns are prevented from sliding against each other because they are attached permanently by electrical contacts. Specialized textiles, with a high density of electronic components and yarn-to-yarn interconnects, may be acceptable for

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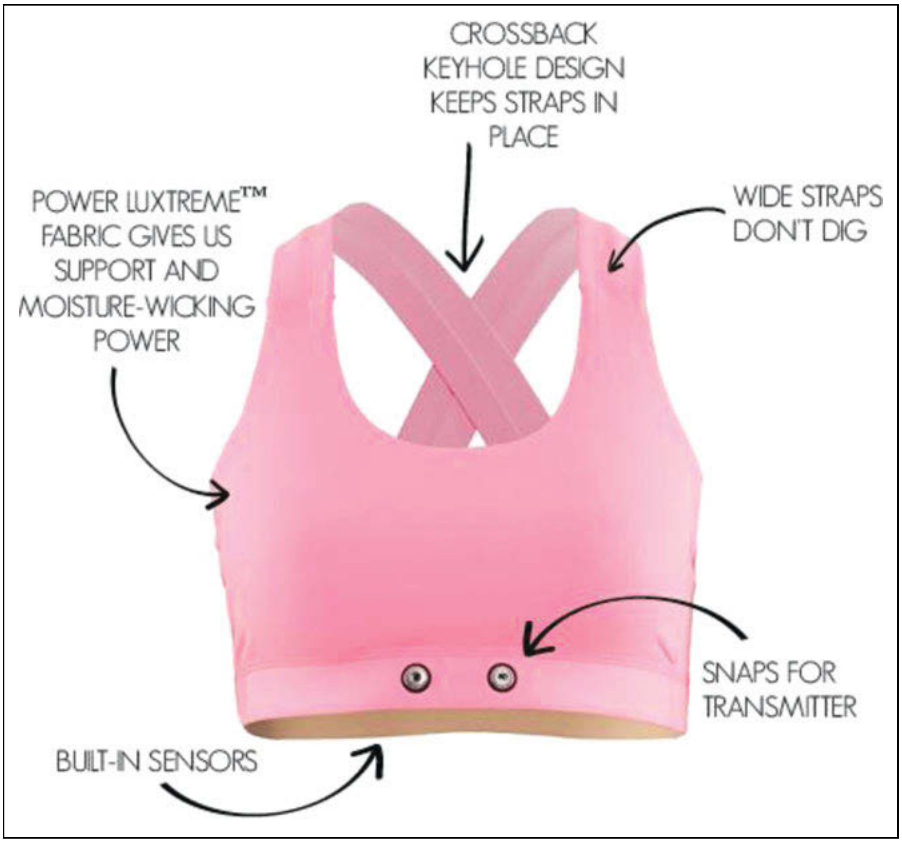

Fig. 1: *The Lululemon All Sport Bra comes with built-in sensors for heart-rate monitoring and snaps for a transmitter. Image courtesy Lululemon.*

professional users. However, to appeal to the consumer market, conventional electronic components and wiring must be introduced as sparsely as possible to ensure a comfortable hand.

In the future, fabric will no longer exclusively play the role of scaffolding for discrete and primarily rigid electronic components but will itself have inherent electronic properties. Then wearables will be particularly well placed to benefit from the experience and manufacturing infrastructure of flexible electronics. Active devices based on weaving together conductors, insulators, and semiconductor fibers will form the basis of these second-generation wearable systems. There already have been numerous demonstrations of this concept, including transistors formed by depositing pentacene on top of a woven network of metallic fibers,[1] transistors made from two crossed fibers coated with PEDOT-PSS with an electrolyte placed at their intersection,[2] and a circuit made from transistor and conductor fibers.[3] Similarly, a wide range of sensors with a fiber form factor have been demonstrated, including light sensors based on optoelectronic fibers[4] and acoustic sensors made from piezoelectric fibers.[5] Compared to first-generation wearables based on embedding rigid discrete electronic components in a fabric, wearables incorporating electronic fibers have great potential for enabling electronics that seamlessly integrate into everyday clothing. Nevertheless, much research is required both at a materials and systems level in order to make these novel devices meet the scalability and reliability requirements of a commercial product.

A Hybrid Architecture of Thin-Film Electronics and CMOS

At the systems level, wearables can leverage architectural solutions from the field of flexible large-area electronics. In particular, hybrid technologies that combine the best of CMOS and flexible electronics are especially well adapted to wearable systems. Table 1 shows the functionality division on an architectural level that our research team developed for this technology. In such architectures, CMOS is primarily responsible for computation, leveraging far faster and more-energy-efficient transistors than its thin-film counterparts. Flexible electronics provides a wide array of sensors and output devices for human–computer interaction so as to enable interfacing with the macroscopic world. Also, it has the capacity to cover large areas with energy-harvesting devices, such as solar cells, for self-powered systems. We have been able to demonstrate the viability of such architectures by building a hybrid system for structural health monitoring.[6] In this implementation, the large-area side features amorphous-silicon TFT-based sensors and access control circuitry, as well a flexible solar cell and associated thin-film power electronics for self-powering. The CMOS IC is responsible for sensor read-out and sensor-data processing, as well as for controlling the system's subcomponents.

In terms of form factor, these hybrid systems are highly versatile because the thin-film sensors and output devices can be spread over the large surfaces of many materials and topographies, such as plastic foil or even paper. The display industry has led the way to batch processing, with substrates approaching 10 square meters. Current efforts to introduce additive printing and roll-to-roll processing of electronics will eventually raise throughput and reduce cost to levels that enable mass-

Table 1: Functionality divisions between flexible electronics and CMOS for hybrid systems are compared with regard to sensing, self-powering, and computation.

Flexible Electronics	CMOS
+ Diverse/conformal sensors	+ Precision instrumentation
+ Large devices harvest substantial power	+ Power management
- Low performance	+ Large-scale integration, energy-efficient transistors

market production. CMOS integrated circuits having a rigid form factor can be sparsely distributed to carry out computational and control functions.

Non-Contact Connections and Low-Wire-Count Interfaces

One of the key challenges of wearable electronics systems is connecting the different electronic components that are embedded in clothing. When designing hybrid large-area systems, we approached this problem by developing two complementary approaches for interconnects. These allow us to robustly connect different planes of the system, along with connecting CMOS ICs and flexible electronic circuits. First, we rely to a large degree on capacitive and inductive electrical connections instead of hardwired connections. Second, we reduce the number of CMOS–to–sensor-array wire interconnects, so that typically there are only 3–5 interconnects when controlling between 10 and 100 separate sensors (Fig. 3).

Figure 2 shows a schematic of the physical architecture of our large-area sensor systems. In these systems, discrete subsystem sheets are laminated together to form a single multilayer sheet. The functional thin-film subsystems are fabricated on sheets, and the CMOS IC is mounted on its own sheet. The sheets are laminated and are up-and-down interconnected inductively, as most are in Fig. 2, or capacitively, as denoted with the top electrode plate in Fig. 2. Not shown is a large passive sheet that provides in-plane interconnection for all functional sheets above and beneath.

Important to note is that the number of wires connected to the IC is small. This is made possible by specialized thin-film circuits on the functional planes. These consist of sensor arrays, scanning circuits, oscillators, rectifiers, battery-charge controllers, and circuits for sensor calibration and data compression. The sensor arrays aside, these circuits have few components and are small enough to be made on yarn without stiffening it excessively.

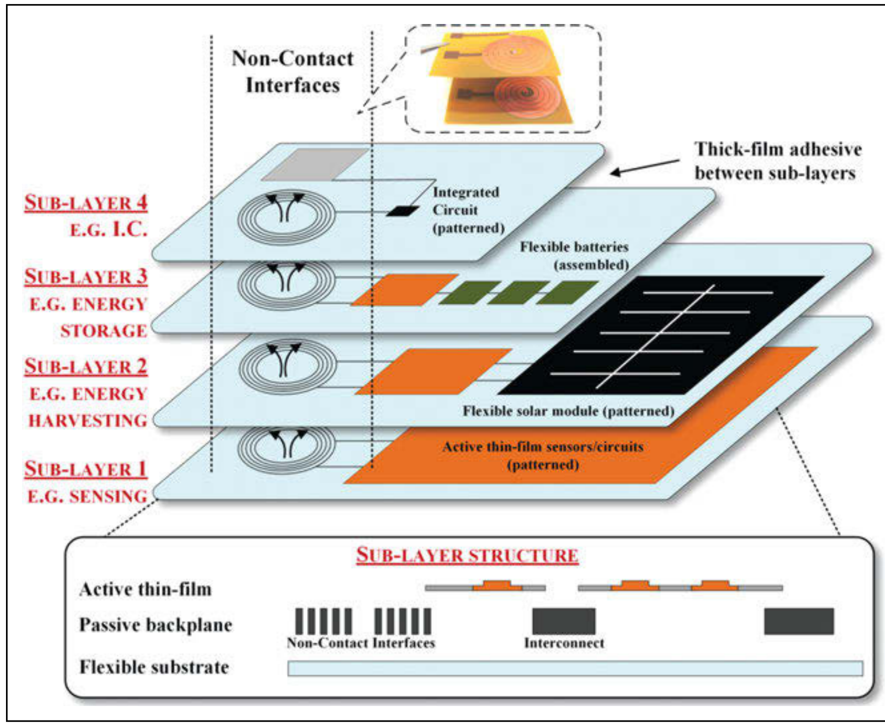

Fig. 2: A schematic of the physical architecture of an autonomous flexible large-area strain-sensor-array sheet system shows four sub-layers.[7]

The architecture of the TFT-based strain-sensing sheet is shown in Fig. 4. In our architecture, sensors are sequentially polled using a custom scanning circuit, fabricated on the

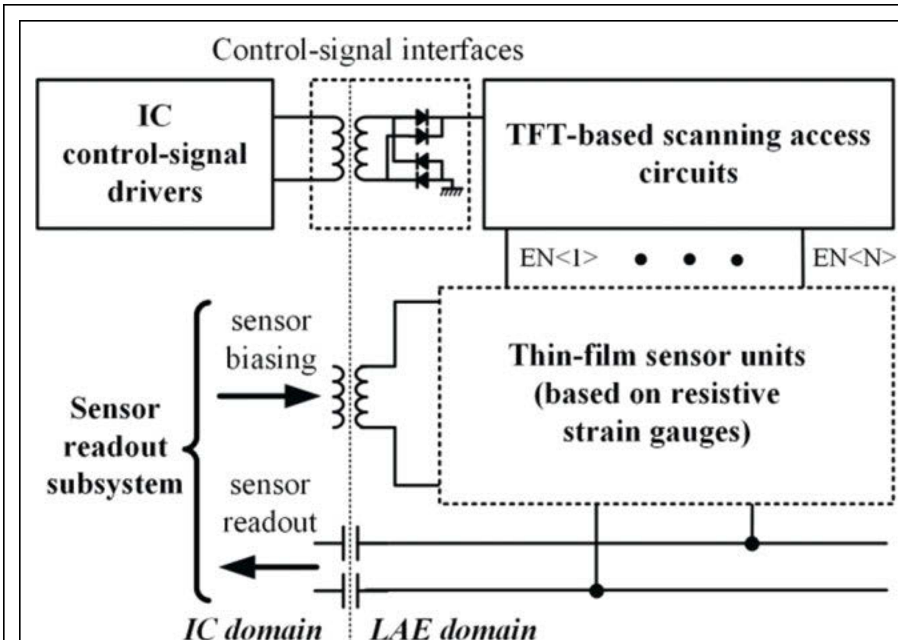

Fig. 3: A strain-sensing system incorporates inductive and capacitive signal transfer from a CMOS chip (IC domain) to a large-area flexible sheet (LAE domain). This system uses only two inductive and two capacitive interfaces.[8]

same substrate with the same technology as our TFT-based sensor elements. By reading out sensors in a multiplexed manner, we can transmit data from the large area to the CMOS domain over a single connection. Due to the modular nature of the scanning circuit, a single circuit can support *N* number of sensors. However, in practice, the number of sensors that can be polled is limited by the maximum sampling rate of the scanning circuit, which in the case of an amorphous-silicon implementation is in the kHz range (~1 kHz for a fully passive scanning circuit[6] and ~10 kHz for a powered scanning circuit). In addition to the signal connection, a small number of control connections are also required.

As shown in Fig. 4, the connections between the large-area electronics (LAE) and the CMOS domain physically consist of capacitive and inductive links, which can be used to transmit both signals and power. Because no mechanical and ohmic connections are involved, in a wearable application, yarns containing insulated electrical conductors would be left free to move against each other. In order to transmit signals from the LAE to the CMOS domain via inductive or capacitive links, the signals need to be converted from DC to AC. This step is carried out by a TFT-based Gilbert modulator, which amplifies the signal from the TFT strain sensor and also modulates it from DC to AC.

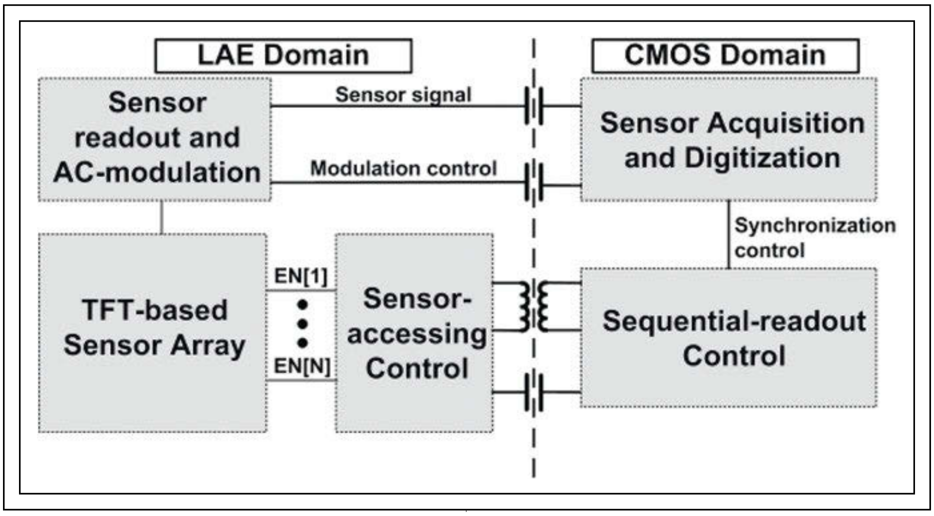

***Fig. 4:** In this architectural block diagram of the strain-sensing subsystem, TFT circuits in the large-area electronics (LAE) domain enable interconnecting with the CMOS domain over as few as four points. The library of thin-film circuits includes oscillators/power converters, scan chains, and instrumentation amplifiers.[6]*

Form Factors of Components Are Adaptable for Wearables

Many of the devices employed in the system illustrated in Fig. 4 are small; examples are diodes and transistors. Others, such as capacitors, inductors, solar cells, and thin-film batteries, are large. Whether small or large, their footprint must be changed from 2-D to 1-D to naturally conform with the yarn of wearables. In many cases, one can go from large-area 2-D components to textile-compatible 1-D components by simply resizing the component. Metalized fibers cut from metal-coated polymer film and then edge-sealed are available commercially in thicknesses down to 20 µm, which is in the range of fine fibers spun to yarn for clothing and textiles (fibers are spun to yarn; yarns may be plied to thread; yarns or threads are woven or knitted to textiles). Two-sided metallization will convert such fibers into capacitors. The dimensions of the thin-film active devices used for sensors, amplifiers, and rectifiers also are commensurate with fine textile-grade fibers. A fine fiber with a circumference of ~ 50 µm will easily accommodate a TFT, as illustrated in Fig. 6. Note that textile yarns, which are spun from fibers, have diameters in the low 100-µm range. Sparsely woven yarns containing one electronic fiber will have a minimal effect on the hand of the textile. An example of a knit fabric that incorporates wire is shown in Fig. 5.

While some of the physical implementations of large-area system components are easily adapted to wearables, others pose challenges. The challenges derive in part from physical principles and in part from physical implementation. Capacitors and inductors illustrate the challenge. By their physics, both are inherently 2-D devices. But both can be made in physical implementations that are close to 1-D. Synthetic fiber cut from film with two-sided metallization can be configured as 1-D capacitors, and close to 1-D micro-inductors can be made from commercial copper on flex. While these will transmit low-power signals, in 1-D fiber format they will be too small for contact-free transmission of power, even in the mW range. While solar cells on fiber have been demonstrated, DC interconnecting such PV fibers would make the fabric too rigid, and wire-free AC interconnection would require the integration of oscillators on each PV fiber. Batteries rely on volume and are therefore inherently 3-D devices. Most likely, solar cells and batteries will have to be integrated into autonomous wearables as patches or in pockets.

Power Savings of Body-Length Wiring

When spun as part of a yarn, fine insulated metal wires can enable considerable power savings over wireless intra-wearable links. This may become an important advantage for

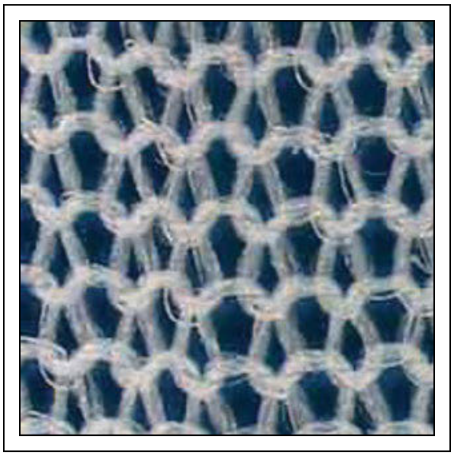

***Fig. 5:** This jersey fabric is woven from a yarn of polyethersulfone fiber, blended with 25-µm-diameter silver-plated copper wire. Image source: http://www.swicofil.com/elektro_feindraht_applications.html*

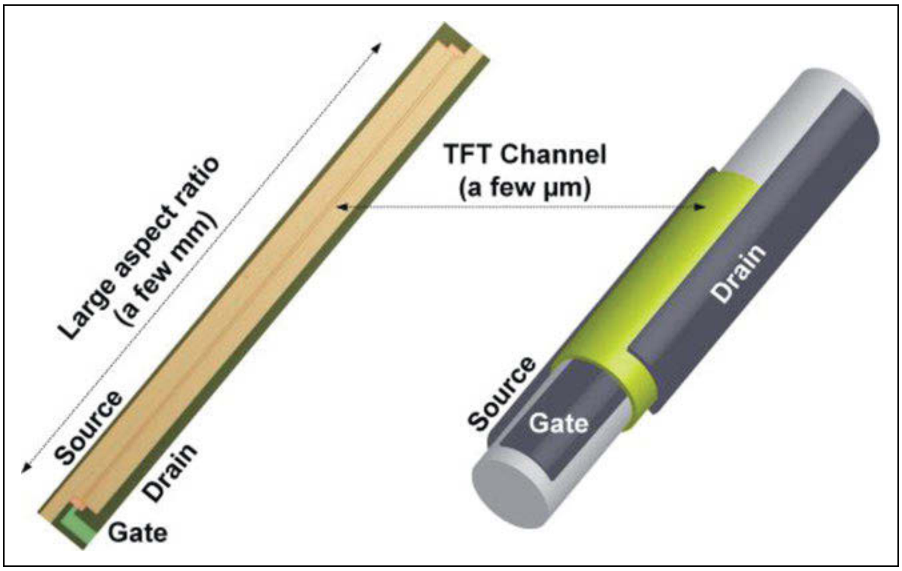

Fig. 6: Left: Today's typical TFT used in large-area circuits may be millimeters wide but is only tens of micrometers long (in TFTs, "length" is measured in the direction of current, from source to drain). Right: The TFT's footprint fits the circumference of a fine textile fiber, which is ~ 50 µm.

autonomous wearables. For our work on large-area electronics, we determined the energy per transmitted bit over body-length wire interconnects. The top portion of Fig. 7 shows the experiment, where transceivers (Tx/Rx) are interconnected via inductive couplers and copper-on-plastic wires. The bottom portion of Fig. 7 shows that communication over wires needs considerably less energy per bit than wireless communication. This approach to wired communication leverages the modulation of digital data, ensuring strong coupling over the inductive interfaces and, with modulation performed to the resonant point of the interconnect and coupler network, minimizing transmit energy, thanks to maximized effective impedance. Because the wire impedance may vary during the use of wearables, the Tx/Rx ICs must be capable of self-adjusting the modulation frequency to match the resonant point of the wireline impedance.

Wearables as Part of an Ecosystem of Electronically Enhanced Spaces

Flexible displays and other large-area interfaces are in a unique position to complement the limited I/O capabilities of current wearable products and augment their ability to interact with the external macroscopic world. Large-area I/O interfaces, distributed throughout public spaces, could add much value to wearable products by seamlessly connecting with them. The small form factor of many current wearables, such as smartwatches or bracelets, means that the most common I/O devices they can adopt are small displays and

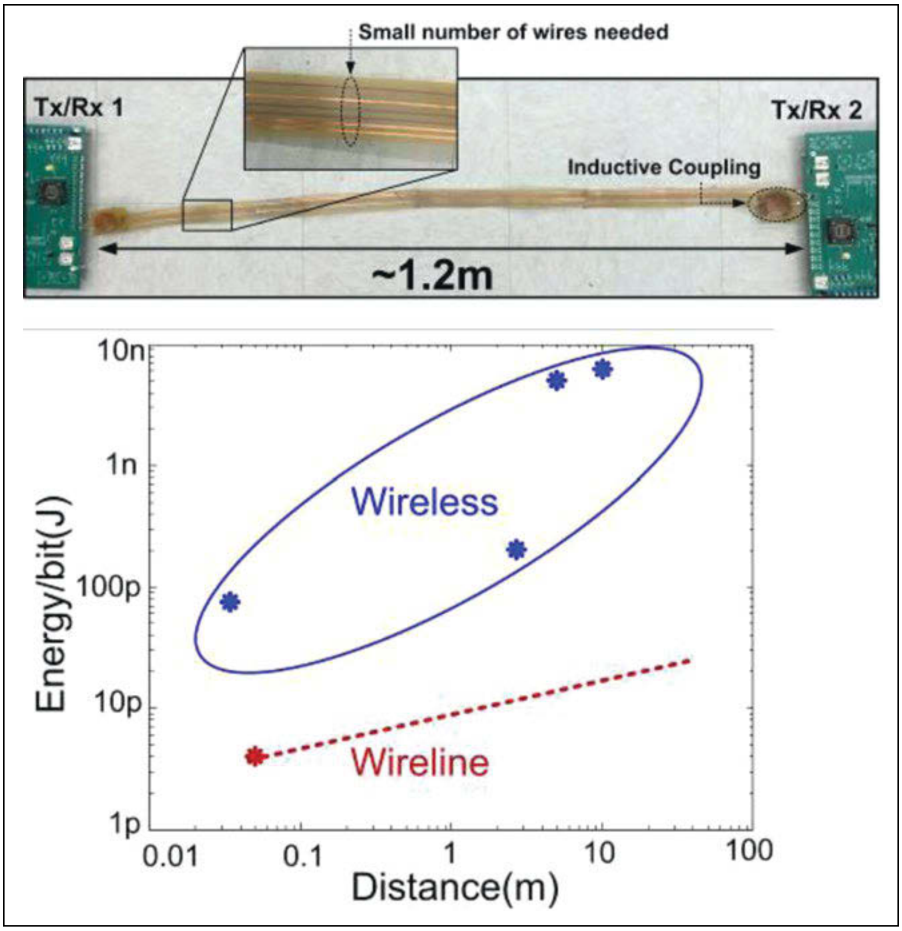

Fig. 7: At top is shown a test of power requirements for low-voltage AC transmission over wires configured for large-area electronics. At both ends of the interconnects, the signal is coupled inductively to transceivers. Bottom: The red line traces the energy needed for transmission over a wire, while the blue data points show published data for wireless transmission.[9]

microphones/speakers for audio interaction. The small size of the displays forces developers to design simplified graphical user interfaces (GUIs), which restricts the complexity of software for these devices and can lead to an awkward workflow for users. Similarly, audio interfaces are hampered by the lack of accuracy of voice-recognition technology, even though significant advances have been made over the last 20 years. Even if wearable products were to be scaled to cover an entire body, accessing certain I/O devices, such as a display, could still be inconvenient.

In the future, we believe one of the greatest opportunities for wearable electronics comes not from viewing them in isolation, but rather treating them as one of the building blocks for an electronic ecosystem. With the development of large-area electronics and low-cost manufacturing techniques, electronics are becoming ever more ubiquitous. It will eventually be viable for public spaces to have ambient large-area displays and other I/O devices readily available for users. These large-area interfaces could seamlessly connect with wearable devices to provide increased functionality for the user. For example, a person could use a wearable smartwatch to monitor heart rate when exercising at the gym. Instead of incurring the inconvenience of a person looking at a watch while exercising, the information could be wirelessly transmitted to a wallpaper-format display, located on the nearest wall. Furthermore, instead of trying to control the smartwatch through its own small touch screen, the watch could interface with a large-area gesture-recognition system.

To harness the full potential of wearables, technology developers should focus on applications that treat wearables as part of an ecosystem with ever more ubiquitous electronics. In doing so, they can benefit from the rich knowledge base and manufacturing infrastructure offered by flexible electronics.

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