Enabling Smart Wearable Technology: Flexible, Stretchable Interconnect

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Abstract

Breakthroughs in wearable electronics are driving exciting, innovative applications in the health, wellness, safety and entertainment markets. But as the user experience matures, product design is driven as much by fashion and style as it is by form, fit, and function. The human-centric element has created a paradigm for the printed circuit, interconnect designers and fabricators. No longer is the printed circuit a mechanically static, controlled-environment technology. Now it must survive continuous dynamic stresses brought on by flexing, bending, twisting, stretching and dropping in an uncontrolled use environment. This article highlights the current and forward-looking interconnect technologies enabling the stream of amazing new smart wearable electronic devices connecting the user to their personalized experience.

Background

Wearable technology is not new. Anyone who experienced the 1970s remembers the Mood Ring, designed with a thermotropic liquid crystal material inside or surrounding the stone of the ring that changed color as the wearer's body temperature changed. The colors inferred the various moods of the user: blue for calm, violet for happy, black for tense, and so on. The wearer had visual feedback with which they could choose to alter his mood.

The advent of the Internet and the World Wide Web began to revolutionize culture and commerce, initially through instant communication such as electronic mail, instant messaging, voice over Internet Protocol (VoIP), social networking and online shopping. By the late 1990s, physical objects (things) were embedded with electronics, such as software and sensors, and connected to the Internet and thus the Internet of Things (IoT) was born.

According to Gartner Inc., by the year 2020, there will be approximately 26 billion devices on the Internet of Things[1]. In 2014, the Pew

Research Center Internet Project canvassed technology experts and Internet users about the evolution of embedded devices and the Internet/Cloud of Things by 2025. Eighty-three percent of the respondents agreed that Internet of Things will have widespread and beneficial effects on the everyday lives of the public by 2025[2].

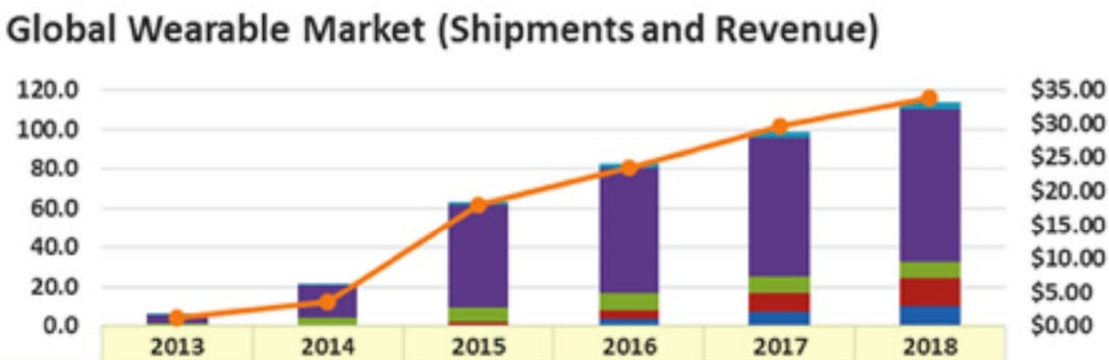
According to the *Global Wearable Technology Market Research Report 2018,* "The global wearable technology market stood at USD 750.0 million in 2012 and is expected to reach USD 5.8 billion in 2018, at a CAGR of 40.8% from 2012–2018. North America is expected to maintain its lead position at 43% of the global wearable technology revenue share in 2018 followed by Europe"[3]. And from the *Wearable Electronics and Technology Market by Applications,* "The overall wearable electronics and technology market is estimated to grow $11.61 billion by the end of 2020 at a compound annual growth rate (CAGR) of 24.56%, from 2014 to 2020"[4]. Based on current market analysis and technology spends, wearable technology is anchored in the future of the IoT.

With the evolution of the IoT, advancements in personal computing technologies have driven printed circuit and printed electronics technology enhancements, power management improvements, wireless module development and overall miniaturization, creating mobile communication devices that fit in the palm of one's hand. The smart phone has enabled personalization of information, social connections and entertainment.

Today, wearable technology has enabled smart, connected devices for personal health and wellness, enhancement of one's safety and the ability to form an individualized entertainment experience. This personal ecosystem is often hubbed by one's smart phone, with information stored on the Cloud and conveniently shared with social networks. The Internet of Things is morphing into the age of the "Intelligence of Things™." As more and more wearable electronics connect to the Internet and provide electronic feedback to support our health, wellness, safety and entertainment decisions, this phenomenon is driving the next age—one of smart, connected living. Figure 1 highlights the estimated shipments and revenue by wearable technology application.

Advancements in Interconnect Design and Materials

Over the past few decades, the computer industry sifted into various subcategories—PCs,



	2013	2014	2015	2016	2017	2018
Other	0.3	0.5	1.7	2.4	2.9	3.8
Wristwear	4.5	16.5	52.5	64.3	71.0	77.8
Modular	1.4	4.1	6.7	8.2	8.3	8.0
Eyewear	0.0	0.0	1.6	4.5	9.9	14.7
Clothes	0.0	0.0	0.6	3.6	6.8	9.6
Total Revenue ($B)	$1.20	$3.60	$17.90	$23.50	$29.70	$33.80

Figure 1: The global wearable market[5].

laptops, tablets, etc. So, too, are wearable electronics becoming categorized, not so much by function as by proximity to the user. Wearable electronics are designed into many forms for body adaptation such as a wristband, apparel, footwear, jewelry, patches, earwear and eyewear. The proximity of the wearable electronic to the user is often categorized into three areas reflecting the level of body contact by the product: close to the body; on the body; and in the body. Figure 2 depicts the wearable electronics body contact level and type of product per category.

With any new technology, eventually certain standardizations become clear. The development of technology building blocks has enabled some manufacturers to develop smart component strategy and accelerate their time to market for certain products.

In creating a wearable electronic product, seven technology building blocks are considered: security and computing; sensors and actuators; human machine interface; connectivity; smart software; battery and power; and flexible technologies and miniaturization. Figure 3 depicts the technology building blocks for wearable electronic products.

Flexible Technologies

Flexible interconnect technologies and component miniaturization are enabling the wearable electronics market. The vast majority of wearable electronic products have printed circuits or printed electronics. There is a distinct difference between these interconnect technologies. The choice of a printed circuit versus a printed electronics technology in a wearable device is driven by form, fit, function and cost. The design and material combinations thereof can thus provide rigid, flexible and/or stretchable electronic solutions.

Rigid PCBs, flexible printed circuits (FPCs), and rigid-flexible circuits (RFPCs) are considered printed circuit technologies. PCB, FPC and RFPC are primarily fabricated using conventional methods of circuit formation of electrical interconnect features by etching copper sheet and lamination with dielectric materials[6]. High-density interconnects (HDI) and every-layer interconnect connection (ELIC) PCBs combined with FPCs form a complex RFPC are more recent technologies that have enabled higher functionality demanded of advanced smart connected wearable devices[7]. Figure 4

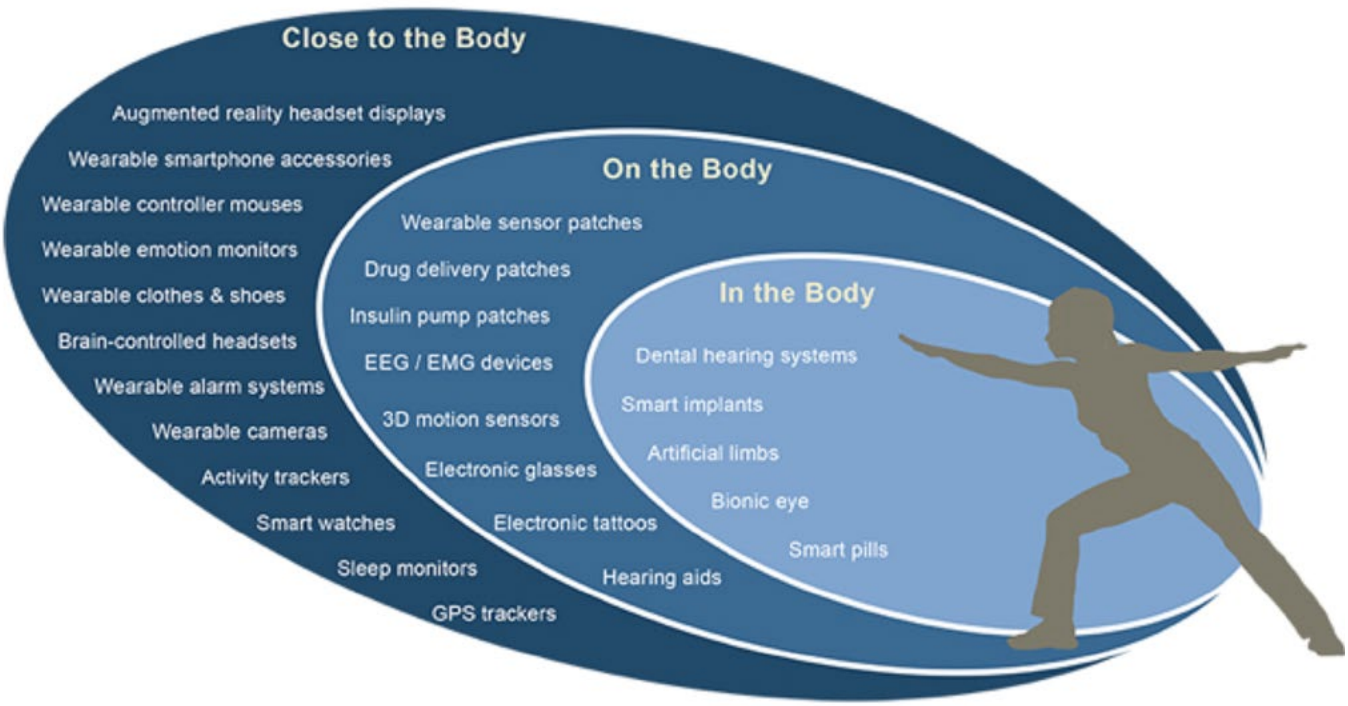


Figure2: Proximity categories of wearable technology. (courtesy of Multek Technologies Ltd.)

represents an RFPC. This figure illustrates a multifunctional rigid board capable of being folded over on itself, reducing the size to a very small stacked package.

Printed electronics utilize printing methods such as screen printing, gravure, and inkjet printing to create interconnects on various substrates. Conductive inks and pastes are used as the electrical circuit material pattern that is deposited onto the substrate. Printed electronics may often be less expensive than printed circuits due to processing and materials although complexity in design and performance drive the costs. Printed ink resistance or frequency characteristics are different from solid copper. In deciding to use printed electronics, the semiconductor component operating voltage and impedance-related (or transconductance) de-

Figure 3: The technology building blocks of wearable electronics. (courtesy of Flextronics Corp.)

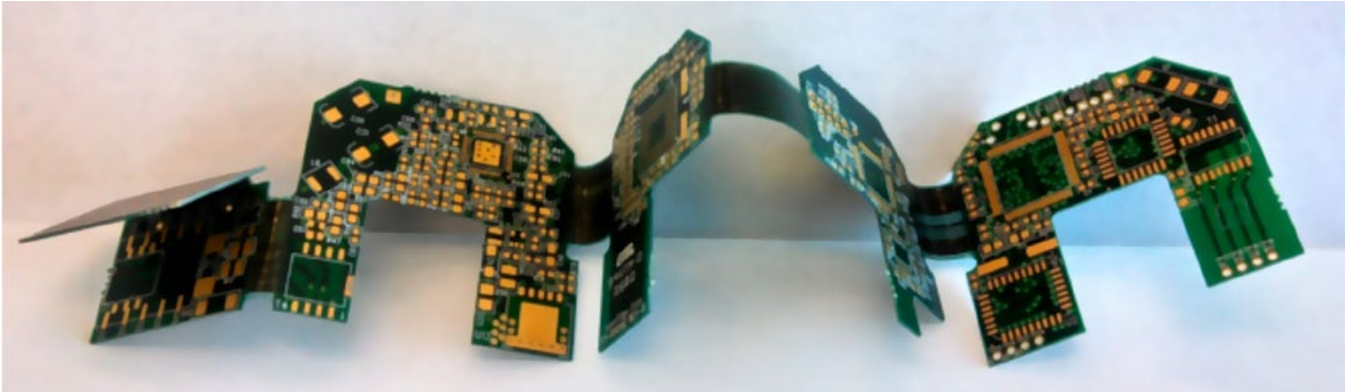


Figure 4: Rigid-flexible printed circuit.

sign requirements must be understood. Also, for any wearable device, the materials' exposure compatibility with the human body surface and fluids must be comprehended, especially for on-the-body and in-the-body applications.

Referring earlier to the proximity categories (Figure 2), the choice of interconnect technology, design and material is defined by these categories. FPCs, RFPCs and printed electronics technologies are often used to take advantage of the flexibility requirements in wearable electronic devices. There are two ways to incorporate these technologies.

1. Flex to fit: The circuit is flexed once only to fit into the assembly.
2. Dynamic flex: This circuit will not only flex to fit into the assembly, but will be dynamic during operation[8].

Multiple applications in each proximity category have high mechanical demands on the interconnects. For example, interconnects in a wristband application must account for constant flexing and twisting during frequent application and removal from the wrist. The electronic patch (electronic tattoo), adhered to the skin, must move with the body, withstand human sweat, moisture and temperature during bathing and daily use. In each example, dynamic stresses are evident.

Stretchable Electronics

Advances in design and materials allow for stretching of the interconnects to mitigate the higher stresses and strains experienced by the circuit in certain wearable devices. In FPCs and RFPCs, higher ductility copper and optimizing the elongation of the dielectrics often addresses the interconnect reliability required. There are more harsh dynamic stress and strain conditions observed in a hinge area of smart eyewear, movement of smart apparel, or in soles of smart shoes. In these cases, the FPC and RFPC can be designed to stretch. The design employs meandering sections to allow a stretching and twisting movement. Figure 5 depicts a meandering design as one of many interconnect design options. The current challenge of designing a meandering structure is the limitation of commercial PCB/FPC design layout software to provide ease of use meandering solutions. The majority of the stretchable interconnect design software is proprietary and specific to a small application range.

In printed electronics, several advances in pastes, inks and substrates are supporting the advancements in stretchable solutions. Polyesters and polyimides are common substrates for printed electronics.

Elastomeric substrates such as polyurethane and polydimethylsiloxanes are providing stretchable options. Silver inks form the majority of the conductive circuits in printed electronics applied to stretchable substrates. The advanced nanoparticle technology of these inks supports a degree of movement of the interconnect. Figure 6 illustrates silver printed ink patterned on an elastomeric substrate.

Stretchable electronics may combine traditional printed circuits and printed electronics. For example, multiple PCBs can be connected

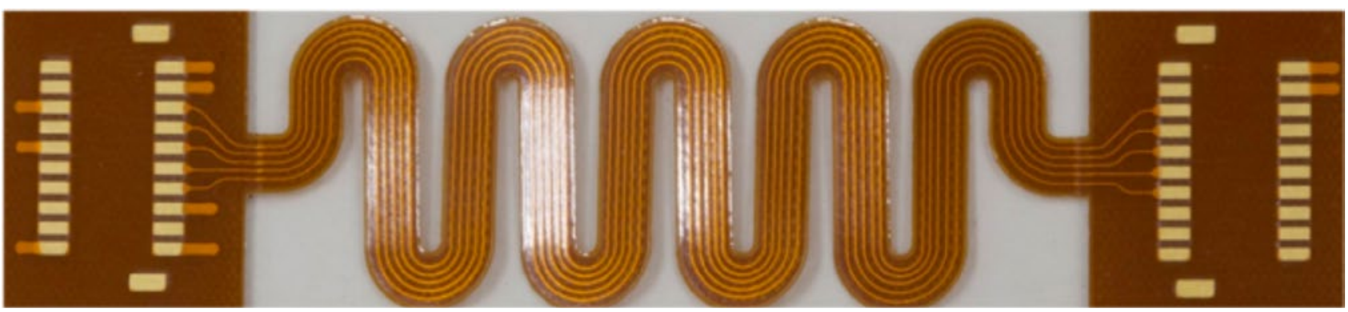


Figure 5: Flexible printed circuit designed with meander for stretch and twist. (courtesy Multek Interconnect Technology Center)

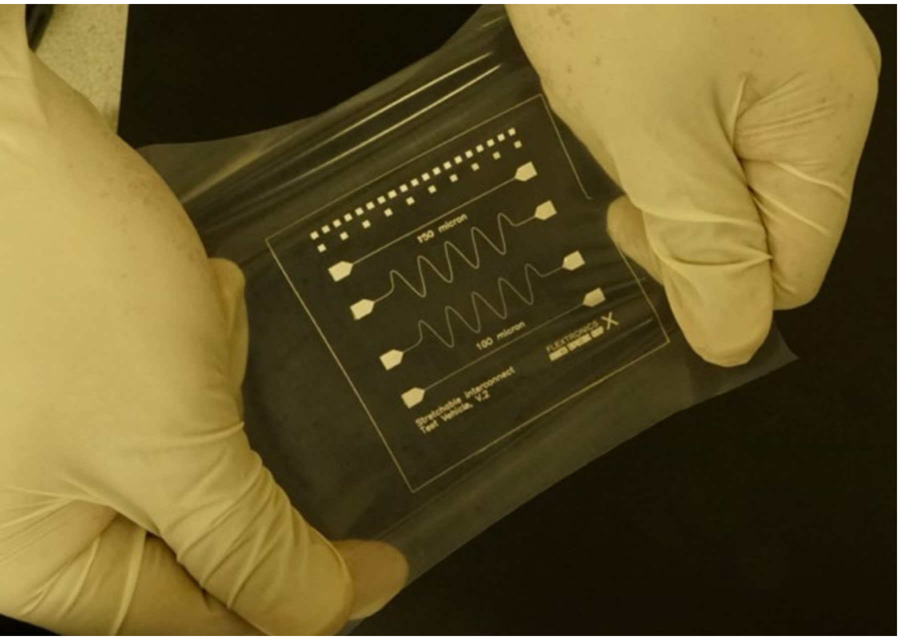


Figure 6: Example of a stretchable printed electronic circuit, with Ag printed ink patterned on elastomeric substrate. (courtesy of Flextronics Advanced Engineering Group)

in a matrix with stretchable copper conductors similar to Figure 5 where the PCBs act as functional islands where the surface mount components are adhered and then the entire PCB island matrix is encapsulated with a protective elastomeric material. This design affords the entire system to be stretchable. The final wearable device may be used for close-to-body or on-the-body applications.

As explained by Wagner and Bauer[9], design configurations for stretchable circuits includes waves, meanders, conductive particles embedded in an elastomeric matrices, meshes and other. The design challenges include protecting the stretchable circuit from exceeding its elongation to break. The solution is to design the wearable device as a stretchable system.

Summary

As breakthroughs continue in wearable technology, any one of these interconnect technologies could leapfrog past the others in terms of usability and applicability. Printed circuits and printed electronics have advanced wearable technology market. These interconnect technologies have enabled the growth of stretchable electronics solutions. The future of flexible and stretchable circuit technologies will require advancement in materials, standardized commercial design software and equipment for advanced assembly and a broad systems understanding by the product designers to account for continuous dynamic stresses and strains brought on by flexing, bending, twisting, stretching and dropping in an uncontrolled use environment. **PCB**

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