Flexible and Stretchable Electronics – Progress, Challenges and Prospects

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For the last sixty years, miniaturization of electronics fabricated on prominent active electronic materials like silicon, germanium, III-V materials and gallium nitride has enabled modernization of today's world - bringing convenience, safety and efficiency in our daily life. However, we are in continuous pursuit to find out alternative materials and process technologies to lower the cost of manufacturing and to increase functionalities of electronics. A radical physical change from rigid electronic components and systems to a mechanically compliant, flexible and stretchable version will jettison the architectural mismatch with nearly all natural lives, enhance the functionalities of existing applications and will usher into new applications, which are not possible today. In this article, we will briefly focus on key areas of this emerging area of electronics.[1–3]

Materials

In 1962, Henry Letheby reported the first organic conductive material. Due to its natural compliance, researchers focused on using available soft polymeric materials as the vehicle for flexible organic electronics. In the year 2000, the Nobel Prize was awarded for discovery of a large set of conductive polymers followed by subsequent promising progress in the area of large-area low-cost thin film transistors and organic light emitting diodes.[4–6] Thousands of scientific papers have been published and hundreds of start-up companies have been established since then. As of today, therefore, organic and molecular electronics are considered as the primary hope and home for flexible electronics except for a few unresolved significant caveats: low charge transport ability and thermal instability.[7–9]

In the late nineties, the discovery of fullerenes followed by subsequent progress in carbon nanotubes and in a broad class of nanowires (including semiconducting) excited the research community toward one dimensional materials based flexible electronics.[10–12] Specifically the superior material properties (compared to those of organic materials) and natural compliance (due to their low dimensionality) of these materials led to a variety of flexible device demonstrations including artificial skin-type multi-sensory platforms.[13–15] Relevant process technology including roll-to-roll printing served as catalyst for this progress. Remaining large-area assembly/integration issues have inhibited further progress.

In the middle of 2000s, the scientific community focused on graphene and other two-dimensional (dichalcogenide) materials, which showed the promise of large area coverage (like thin films) and pristine atomic crystal structure with superior charge transport ability.[11,16] These materials have been especially investigated for energy storage, transparent conductive thin film and sensor technology – there have been thousands of scientific publications published. However, non-uniform growth, lack of a suitable interfacial layer to ensure higher conduction and formation of dielectric and conductive interfaces remain as unsettled challenges. Therefore, even with reduced momentum, new two-dimensional atomically thin materials continue to be explored every day to overcome these remaining challenges.

From the very beginning, classical crystalline materials have been ignored for flexible electronics due to their already dominant presence, inherent rigidity and brittleness. However, advances in amorphous, polycrystalline thin films (specially oxide based) opened up an alternate door to use nearly identical material properties (those of traditional materials) for flexible electronics. In this, thin film transistors lead the way. Yet, from the beginning of 2000s, there has been a surge of flexible single crystal silicon, gallium nitride and III-V electronics. Their advantage fabrication using existing complementary metal oxide semiconductor (CMOS) technology makes them attractive. They are fast, scalable and reliable, too.

Another commonly used material, paper, has been explored as a potential host substrate for ultra-low cost flexible electronics. By functionalizing them with chemicals and other low-dimensional materials and processes, a variety of applications have been demonstrated.[17–19] Nonetheless, their reliability has been questioned often. Recent demonstrations of recyclable papers as active electronic materials and their biocompatibility have now brought them back as alternative flexible electronic materials.[20,21]

Design strategies

While innovation in material to achieve flexibility and semiconducting properties require innovative design of composite materials, stretchable electronics really depend on this singular requirement of appropriate design strategy. Stretchable electronics are subjected to maximum physical deformation (linear and non-linear both). Again, the major design strategy has been to use macroscopic stretchable polymeric material as host substrates followed by deposition/transfer of organic, 1D and 2D material on them. While 0D and 1D materials, being nanoscopic, easily conform and comply with stretching phenomena in the host substrates[1,2], 2D materials can rupture based on their mechanical properties. Some popular stretchable organic and

1D materials are silver nanowire (AgNW). Often graphene has been dubbed as a potential active stretchable electronic material.

From the middle of the 2000s, several innovative ways of transforming conventional rigid electronics into stretchable electronics have been successfully developed and demonstrated: pre-straining and adoption of fractal design.[22,23] In the first case, a pre-strained polymeric material acts as a host substrate for conventional crystalline and amorphous thin films (including silicon and gallium nitride) and then the pre-strained material is released to relieve the stress. This transforms the continuous thin film into a seemingly deformed structures (but in reality, regular wavy shaped), but this enables electronics with limited extensibility (up to 10%). In the latter approach, islands of active materials are interconnected/bridged through adoption of various fractal designs (serpentine, spiral, etc.).[24–27] Such creative design adoption has resulted into extensibility up to 1020%. Recently some studies have been exploring out-of-plane, staged/periodic and reversible stretchable platforms for stretchable electronics.[24–27] In all cases, design strategies have to conform the choice of material with suitable properties and deformation and endurance mechanics.

Integration strategies

From the very beginning nearly all efforts have been focused on demonstrating discrete devices. Chipfilm™ has made substantial efforts towards manufacturable flexible CMOS system. The persistent challenges include, but are not limited to, expense and reliability.[28] Several companies, including Xerox PARC, have been pursuing low-cost printing technology development focusing on organic materials. However, none of those has been proven as efficient as CMOS technology although the cost of the latter is obviously higher due to its precision. From a system level integration perspective, Rogers *et al.* have shown multi-sensory platform for various applications including brain-machine-interfacing.[29–31] Someya *et al.* uses active matrix display type architecture for their organic material focused sensory platform.[7,32] Bao *et al.*, Javey *et al.* and Arias *et al.* have demonstrated also variety of multi-sensory platforms.[14,33–36] Hussain *et al.* has led a CMOS based manufacturing strategy which can produce a fully flexible packaged electronic system. They emphasize on a non-planar coin-like 3D architecture where sensors, actuators, energy harvesters and antennae remain in the outer sides of both planes and other accessorial electronics remain in the middle (like in a sandwich) and they are also physically flexible.[37,38] Figure 1 illustrates stand-out devices from these groups in this area.

Applications

- *Display:* Practical organic light emitting diode (OLED) devices were first demonstrated by Eastman Kodak in 1987. Since then both academy and industry have pushed this technology and billions of dollar have been invested. It is expected that Samsung and LG Electronics will launch the first flexible display in the 2020s.
- *Photovoltaic:* Since flexibility is achieved by volumetric reduction, in the case of inorganic material based solar cells, efficiency is compromised. Recently, Hussain *et al.* introduced a corrugation structure-based flexible crystalline solar cells with record efficiency of 19% at a bending radius of 140 μm.[39] Obviously using III-V solar cells will be rational choice for higher efficiency, except they will increase the cost too. Although organic materials based solar cells could have been naturally flexible, their fundamental low efficiency and unreliable operation (until today) impedes their wide scale adoption. Sun Power™ suggests commercially available flexible solar cells from them.

- *Wearable:* Major electronics giants like Apple and Samsung have already acquired a substantial market with their Apple Watch and Samsung Gear. Fitbit became a major player by introducing the first mainstream electronic health tracker. Since then hundreds of start-ups have launched nearly the same kind of products with small variations in the functionalities and major design differences. Their approach is to use miniaturized ICs, but at the end they are not completely flexible (Figure 1 b & d). Also, they are still expensive. Thus, the overall market for truly flexible wearable devices is yet to emerge.
- *Implantable:* Introduction of implantable electronics would be a game changer like what has happened with pacemakers. However, in most cases, rigorous requirements for clinical trial data to prove long-term reliability and safety loom as a critical concern. This serves as a major basis for public perception and doubt about implantable electronics. Current academic research efforts are restricted to brain machine-interfaces and nanomedicine based targeted drug delivery (which by the way is not an implantable device).[40,41]
- *Add-on:* This new kind of electronics introduced by Hussain *et al.* where they envision using Do-It-Yourself integration strategy to assemble low-cost add-on electronics using recyclable materials.[38,42] Such electronics are expected to be attached to existing objects to transform them into "smart" (data and sensing oriented) objects.
- *Soft robotics:* Whitesides *et al.* have introduced the concept of soft-robotics and we can see major innovations and their practical usage through robotic arms and other organs.[43] An effective integration of both the interactive material based soft robotics and flexible and stretchable electronics can add breakthrough functionalities in soft robotics.
- *Textile:* While we have been using textiles for thousands of years, its basics have remained the same for centuries. Therefore, we have observed limited activities to "smartize" them.

However, coarse nature of fabric introduces an interfacial mismatch for traditional electronics to be integrated. And hence, substantial research can be carried out to develop reliable high volume manufacturing strategy for low-cost smart textile.

- *Communication:* Microwave (and millimeter wave) flexible and stretchable electronics are an important sub-field of flexible and stretchable electronics that has demonstrated its impact over the last decade.[15,44–47] Conventional microwave electronics have been widely implemented in mobile devices, wireless communications, radar sensors, radio monitoring and surveillance, etc. However, the present form of microwave electronics is chip-based, which are rigid, brittle, system-bulky, and costly, particularly if implemented in a large area, thereby limiting their applications to be further expanded. For example, a high density array of a millimeter-wave phased-array antenna based on rigid-chip wiring is heavy, costly, and has low reliability. The sub-field of microwave flexible and stretchable electronics was created to specifically address the need of high frequency electronics that can satisfy the requirements of non-conventional form factors (e.g., non-rigid and large area) and overcome the various shortcomings of the present microwave electronics.

In comparison to the conventional circuit board-based microwave integrated circuits (MIC) and extensively implemented monolithically microwave integrated circuits (MMIC) over the last 2-3 decades, the mechanical flexibility and extensibility features of the microwave flexible electronics, which were demonstrated in the recent decade,[48–51] opens numerous new microwave application opportunities that cannot be fulfilled by MIC/MMIC. The unique mechanical features allow the flexible and stretchable microwave electronics to be implemented on uneven or rugged surfaces, wood substrates and skin, dramatically expanding the application boundaries of the traditional MIC/MMIC.[52,53] While the microwave performance has been maintained and the functionalities have been greatly enhanced in microwave flexible electronics, the non-traditional fabrication methods associated with the new form factors have also led to a great cost reduction in comparison to the fabrication of traditional MIC/MMIC.

As a sub-field of the broadly defined flexible electronics, the unique feature of the microwave flexible/stretchable electronics that distinguishes it from the rest of the flexible electronics field is the high frequency (>1 GHz) used. At such high frequencies, new materials, new design methodologies, new fabrication techniques, and new characterization tools are required.[45,46,54] Flexible microwave electronics include active devices, passive components and substrates.[45,46,55] To satisfy the requirements of high frequency operation with mechanical flexibility and extensibility, the substrates suitable for microwave flexible and stretchable electronics need to exhibit low microwave energy loss ($\tan\delta$). As high-frequency operation inevitably causes excessive heat generation, the substrates or any fixtures that are used to carry the active devices on the substrates will also need to have good thermal conductivity.

High-performance active transistors are key components for microwave flexible and stretchable electronics. Single crystal-based semiconductor transistors are the only current material that can fulfill the requirement of high frequency operation. To satisfy the requirements of both high frequency and mechanical flexibility, single crystalline nanomembranes that have been studied for the last decade have been proved to be suitable materials for implementing high-frequency flexible transistors due to their processability, including transferability, scalability and cost-effective production methods.[45] As of today, the frequency figure-of-merit (FOM) of the nanomembrane-based flexible transistors has reached beyond 100 GHz. The impressive microwave power handling capability of these flexible transistors has been demonstrated. [50,54,56]

Satisfying the need for operation in different frequency ranges, both lumped and distributed flexible and stretchable passive components have been demonstrated and implemented in flexible and stretchable microwave and millimeter wave circuits depicted in Figure 2.

Challenges

There are several critical challenges that remain for wide-scale adoption of flexible and stretchable electronics. The first one is need for a go-to application. Obviously major display companies are suggesting flexible displays to be that game-changing technology that requires these electronics. While the display itself is flexible, the associated electronics are still non-flexible. Therefore, it falls under the category of a hybrid architecture. Also, rollability will allow displays to be portable easily, but its pervasive use is questionable. A second area of potential usage is photovoltaic and battery technology. Both can be benefited by the volumetric reduction and subsequent weight savings, flexibility, and low-cost fabrication. However, a critical challenge remains for both in the context of appropriate material selection. Other concerns are long-term endurance and safety. Finally, the lack of coherent manufacturable technology serves as a severe challenge specifically when the overall activity is predominantly led by the academic community. Major integrated device manufacturers are focused on already established technologies and strengthening those further. Hence, a major technological gap exists.

Future outlook

Empowering mankind with flexible electronics can enable a better future for us. That requires electronics, which are low-cost, easy to implement and use. From these perspectives, flexible and stretchable electronics can be promising venues for expansion of electronic applications. While many such applications have been demonstrated, rarely have any of them been commercialized for widespread usage. Therefore, as mentioned before, the identification of critical go-to applications is the key. That will happen with evolution of a robust manufacturing technology. Some impediments exist in the context of implantable electronics including social prejudice and safety related regulations. Innovation in bio-safe materials and appropriate communication can be effective to overcome both.

Conclusion

Regardless of the countless advances in flexible and stretchable electronic components, substrates technology, and applications which have been demonstrated, they are just a tip of the iceberg. A combination of materials, process technologies, and manufacturable integration strategies focusing on effective and impactful applications at an affordable price range will expand the horizon of future electronics to empower humanity and to make this world a better place every day.

Figures

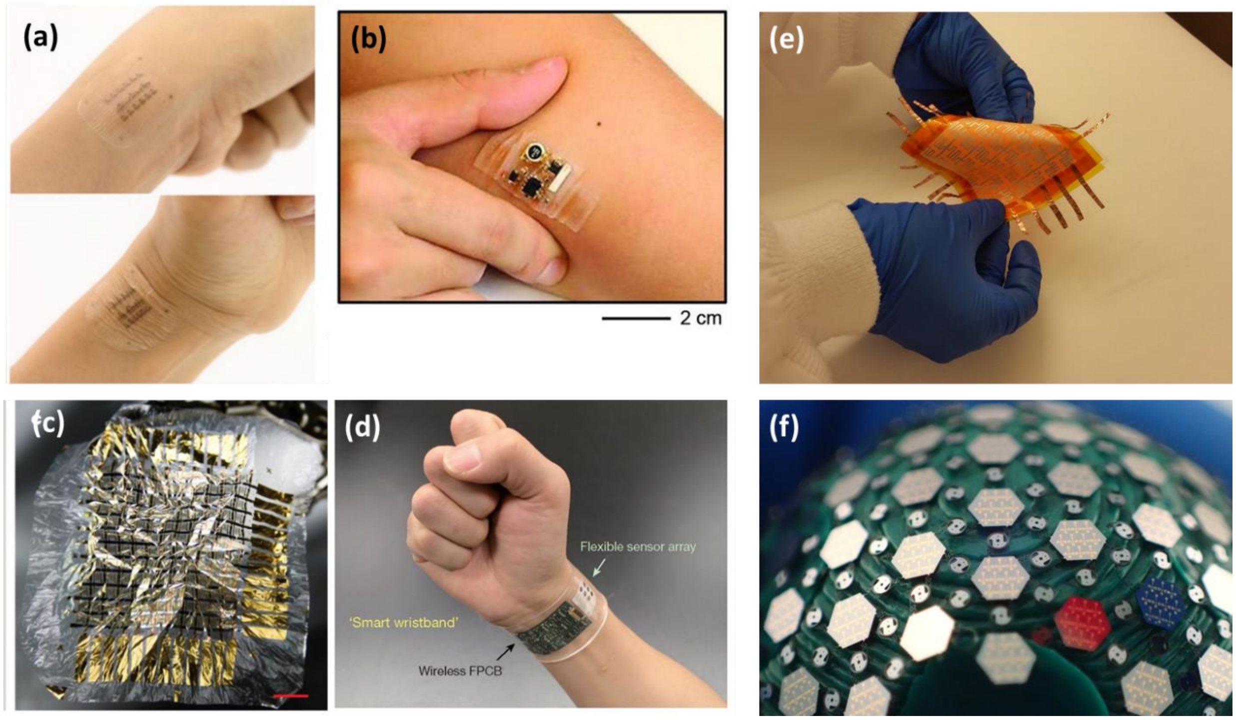

Figure 1: Demonstrations of flexible electronic systems. (a) Intrinsically stretchable organic circuit showing high conformability to a human wrist for functional electronic skin [36], Copyright 2018, Nature Publishing Group. (b) Optical image of the epidermal electrode system for ECG monitoring, [31] Copyright 2014, American Association for the Advancement of Science. (c) Ultraflexibility shown by crumbling nature of the large area matrix sensors with thickness of 2 µm scale bar is 1 cm [32], Copyright 2013, Nature Publishing Group. (d) Digital photograph of the 'smart wristband' showing small flexibility of the sensors array on a flexible PCB platform,[33] Copyright 2016, Nature Publishing Group. (e) Flexible paper-skin platform with multiple functionalities. Reproduced with permission[21], Copyright 2016, John Wiley and Sons, Inc. (f) Fully spherical configuration of flexible photodetectors array for simultaneous 360° imaging systems, Reproduced with the permission of AIP Publishing.

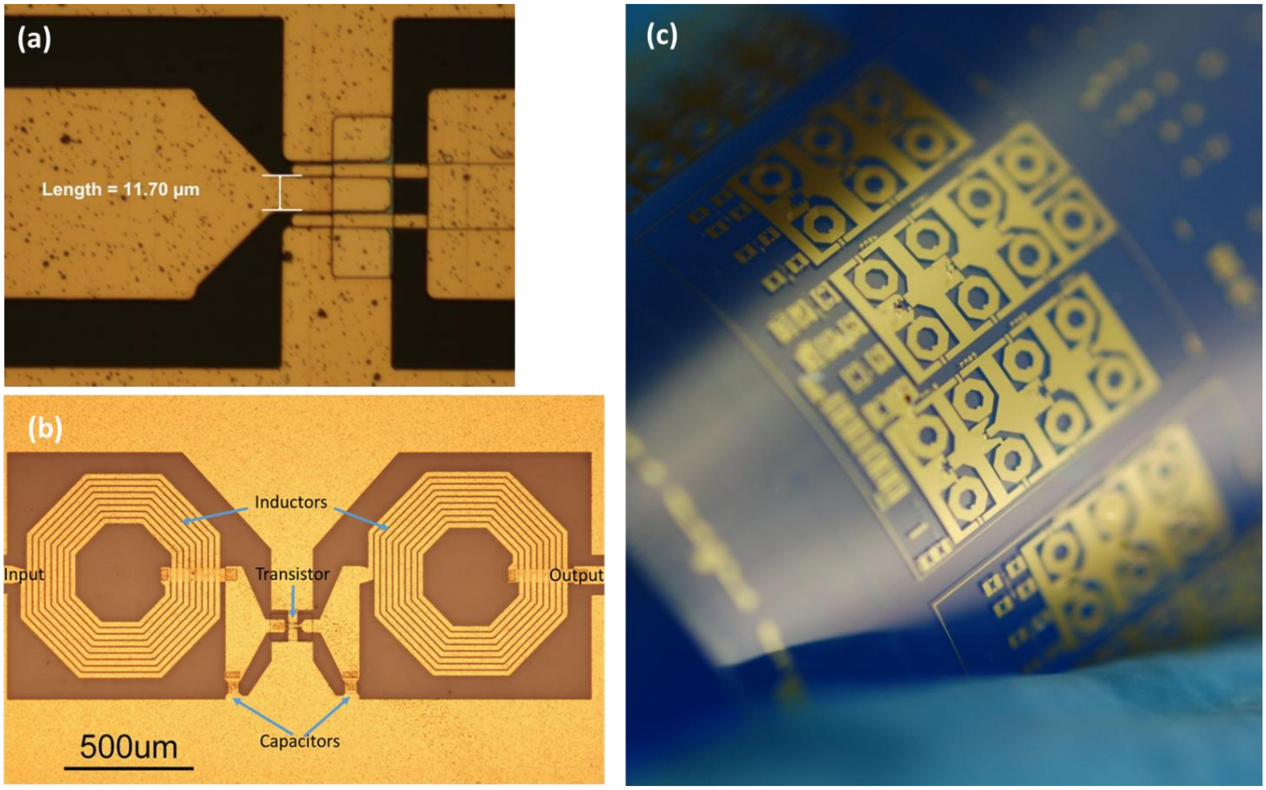

Figure 2. (a) Microwave thin-film transistor fabricated on a PET substrate. (b) A single-stage 1 GHz amplifier circuit fabricated on a PET substrate. The active device area occupied less than 0.5% of the circuit area. (c) An array of microwave amplifiers on a bent PET substrate. Reproduced with permission[56], Copyright 201, John Wiley and Sons, Inc.

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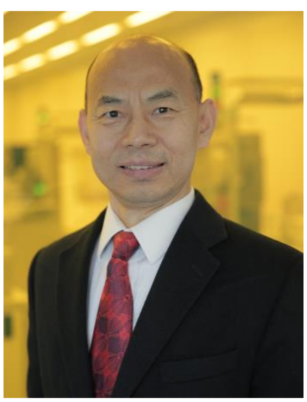

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