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Advances in design and manufacture of stretchable electronics

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Flexible and stretchable electronics present opportunities for transition from rigid bulky devices to soft and conformal systems. However, such technology requires mechanical design and integration strategies to enhance robustness and form factor. In addition, scalable and reliable fabrication pathways are needed to facilitate the high volume manufacturing required to satisfy a growing market demand. This report describes recent advances in design, manufacture, and reliability of flexible and stretchable electronics technology. Flexible concept devices for physiological monitoring are introduced, before discussion of high throughput fabrication of stretchable electronics, then hybrid integration of conventional rigid components on stretchable carrier substrates with an emphasis on a need for further developments in device reliability testing procedures. Finally, consideration is given to transition options for more eco-conscious device constituents. These cases progress flexible and stretchable electronics towards robust, fully integrated, unobtrusive devices incorporating sustainable components. © 2022 The Author(s). Published on behalf of The Japan Society of Applied Physics by IOP Publishing Ltd

1. Introduction

Flexible and stretchable electronics are devices incorporating conductive tracks, circuitry or other electronic components integrated with material(s) capable of mechanical deformations as a result of possessing a low Young's modulus.1) Benefits of flexible and stretchable electronics systems in place of bulky rigid devices are evident in use cases subject to motion and dynamic changing structural form. For instance wearable electronics, which can provide convenient human-machine interfaced2) platforms for monitoring physiological parameters during sports or in clinical settings.3,4) In addition to wearables which are the primary focus of this paper, stretchable electronics find vast applications including displays, energy harvesting and storage devices, and soft robotics, as detailed in recent review articles.5–7)

Significant challenges in mechanical design arise when attempting to develop strain tolerant electronic devices that can be mounted in a conformal manner on non-uniform or moving surfaces while retaining electronic functionality. For instance, a key challenge is robust integration of rigid or printed components on flexible or stretchable carrier substrates. Particularly where scalable fabrication approaches are required to manufacture sufficient volumes of devices with high uniformity for research and development testing and to satisfy increasing consumer demand.8)

In this report, we describe recently demonstrated cases progressing from flexible to stretchable electronics, with an emphasis on reliability and high throughput fabrication methods such as rotary screen-printing and pick-and-place hybrid integration. Finally, we envision a shift towards an eco-conscious approach by integration of sustainable materials.

2. Discussion

2.1. Polymer carrier substrates for wearable electronics

In recent years, a number of strategies have evolved in the development of wearable electronics. Integration of functional 1D structures9) including elastomeric fibers10) into traditional 3D textile forms11) has facilitated the emergence of electronic textiles.12–15) For instance, coating of cotton yarn with polypyrrole to form spring like strain structures for strain sensing,16) or coating stretchable nylon/spandex fabric with poly(3,4,-ethylenedioxythiophene and polystyrene sulfonate acid (PEDOT:PSS) to generate a temperature insensitive wearable supercapacitor.17) Other strategies include the production of composite materials, such as electrically conductive structures embedded in a stretchable matrix,18,19) or incorporation of conductive liquid metal alloys.20–23) Rather than further detailing examples of work reporting textiles, composites, or liquid metals, the scope of this paper is focused on high throughput fabrication, which typically relies on additive processing such as printing of conductive structures, or pick-and-place integration of active components onto a carrier substrate film.

A variety of synthetic polymer materials have been explored for their applicability as substrate materials in conformal wearable devices. Due to a requirement for multi axis mechanical deformations in response to skin movements, an important physical property of materials intended for skin conformability is the Young's modulus of elasticity (E), where a smaller E value indicates a greater degree of flexibility or stretchability. One approach for experimental determination of E is by means of a contact apparatus, which measures displacement resulting from compressive force applied to a sample using a spherical probe. This indentation method enables the measurement of small compressive displacement and force at mesoscale, yielding data that might not be possible to obtain using nanoscale or macroscale equipment.24) Given the condition of Poisson's ratio = 0.5, this approach enables calculation of E according to

$$E = 9W/16\,R^{1/2}(RD)^{3/2}, \tag{1}$$

where W is the load applied to the sample by a spherical probe with radius R, and RD is the measured relative displacement.24) Table I presents a number of materials that have been exploited as carriers for wearable electronics, listed in their respective order of decreasing values of E, from

Table I. Polymeric substrates commonly used for wearable electronics, listed in order of decreasing Young's modulus for comparison with skin in the bottom row.

Material	Young's modulus	References
Polyethylene naphthalate (PEN)	4 GPa	26
Polyethylene terephthalate (PET)	2.5 GPa	27
Polyimide (PI)	2.3 GPa	28
Thermoplastic polyurethane (TPU)	3.6–88.8 MPa	29
Polydimethylsiloxane (PDMS)	0.5–3 MPa	6,30, 31
Ecoflex silicone	50–100 kPa	6, 32
Human skin	Epidermis 140–600 kPa, dermis 2–80 kPa	33

flexible polyethylene naphthalate (PEN) to stretchable silicone. Poisson's ratio (ν) is another useful metric for quantifying the intrinsic mechanical properties of a material. This is an approximation of the ratio of change in axial strain ($d\varepsilon_{\text{axial}}$) to the change in transverse strain ($d\varepsilon_{\text{trans}}$) under uniaxial extension[25] as described by

$$\nu = -\frac{d\varepsilon_{\text{trans}}}{d\varepsilon_{\text{axial}}}, \tag{2}$$

Recently, a method of laser engraving a grid pattern was demonstrated for ascertaining changes in axial and transverse strain, facilitating the experimental determination of a high accuracy Poisson's ratio for polydimethylsiloxane (PDMS) of 0.49989 ± 0.00111.[25] Methods such as this approach are likely to provide accurate experimentally verified Poisson's ratio values for countless other stretchable materials, including those presented in Table I, yielding information on physical properties to assist selection of suitable materials for stretchable electronics design.

2.2. Scalable fabrication of hybrid platforms for physiological monitoring

Electrochemical sensors are useful for rapid analysis of biomarkers.[34] These kind of sensors can be miniaturized, adapted for improved flexibility and stretchability,[35] and integrated into wearables towards personalized healthcare.[36] For example, formed into wearable patches and exploited for sweat analytics.[37] High throughput and low unit cost fabrication methods are required for single-use electrochemical sensor patches to be used in large population studies or commercialized into products. In response to this need, roll-to-roll (R2R) gravure printing was reported for fabrication of electrochemical sensors demonstrated with real time sweat pH measurements.[38] R2R screen-printing is another approach for generating large volumes of printed electronics with high yield on flexible or stretchable substrates.[39] The relative low cost of screens in comparison with gravure plates (or cylinders in the case of R2R process) means that screen-printing can be more cost effective than gravure if there is desire to regularly change print designs, or print many different layout patterns. Furthermore, screen-printing provides thicker layers than is feasible using gravure printing, which is important for generating sufficient conductivity. Electrode structures R2R-printed on flexible polyethylene terephthalate (PET) can be combined with laser-patterned medical adhesive tapes which define fluidic channels, to form conformal wearable skin patches for electrochemical analysis of glucose in diabetes diagnostics,[40] or ions and sweat rate for exercise physiology.[41]

Single use electrochemical sensor patches can couple with miniaturized, wireless and flexible electronic readout devices. This enables a conformal and low profile hybrid electronics wearable platform composed of (i) a single use skin patch part fabricated by high volume R2R printing and laser patterning processes, and (ii) a reusable readout electronics part assembled on flexible polyimide (PI). Figure 1 presents an example of such a platform, which was demonstrated for monitoring of lactate in exercise-induced sweat by chronoamperometry, with data acquisition via Bluetooth low energy to a custom mobile phone application simultaneously from devices worn in four different body locations.[42]

Another example of such a hybrid electronics wearable system was reported for monitoring wound healing by bioimpedance.[44] This device connects a flexible wireless electronic readout system on PI substrate to a 16-channel electrode array, where the silver electrodes are deposited by scalable screen-printing process onto a stretchable, breathable and biocompatible nanocellulose/polyurethane composite substrate[45] for measuring increasing impedance in response to the healing process of a skin wound.

The above-mentioned lactate and bioimpedance monitoring platforms benefit from readout electronics fabricated on industrial standard flexible PI foundations. However, despite somewhat conforming to the skin of the wearer, there is a mismatch between mechanical properties of the device and the skin, such as the Young's modulus (epidermis = 140–600 kPa,[33] PI = 2.3 GPa[28]). This means

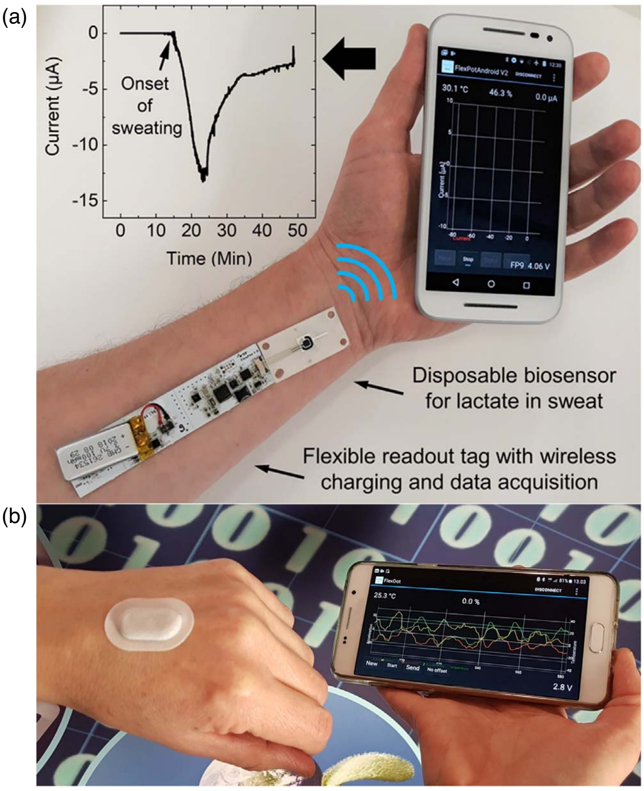

Fig. 1. (Color online) Flexible and miniature wearable devices for physiological monitoring. (a) A wearable system for monitoring lactate in exercise induced sweat.[42] (b) An activity tracker patch with 3-axis accelerometer and shake-to-wake functionality. Images courtesy of VTT Technical Research Centre of Finland Ltd.[43]

that the devices do not stretch in the same manner as skin does, so can restrict movement. In addition, PI and PET components do not allow the skin to breathe, which can lead to accumulation of sweat beneath the device, or skin irritation. Wear comfort of the device could be improved by incorporating porous or moisture wicking components, and by condensing the electronics design to reduce the device footprint and total size of the electronics system. An example of condensed electronics design is an activity-tracking device shown in Fig. 1, which despite relying on a rigid circuit board for the active electronics, measures only 12 × 23 mm^2 including a stretchable medical adhesive, and features a 3-axis acceleration sensor with "shake to wake" function to trigger data streaming by Bluetooth Low Energy to a custom mobile phone app.[43]

Wearable electronics platforms for physiological monitoring can benefit from an improved form factor by integration of stretchable materials to better replicate the mechanical properties of the skin such as low Young's modulus, towards truly epidermal electronics.[33] To this end, the following section describes demonstrated examples of scalable electronics fabrication methods on stretchable substrate materials.

2.3. Considerations for high-throughput fabrication of stretchable electronics

Mechanical properties such as the stretchability and durability of electronic devices are not only determined by the carrier substrate onto which devices are fabricated, but they are also influenced by the attached electrical components and interconnects. Printed silver features formed by nanoparticle inks can possess electrical conductivity 56% or less of the value for bulk silver metal.[46] This can be explained by the particulate nature of the material, which results in some degree of boundary effects between discrete particles, hindering free electron flow. when printed features such as screen-printed nanoparticle silver interconnects are subjected to mechanical stress, fractures can form in the material which cause increased electrical resistance (R) by reducing the cross sectional area available for charge carrier pathways described by[47]

$$R = \sum \rho \frac{l_i}{s_i}, \tag{3}$$

where ρ is the material resistivity, l_i is the length of material for charge carrier transport, and s_i is the cross sectional area of the material.

One strategy for minimizing fracture of printed interconnects is by geometric design of print pattern layout. In contrast to a 1D line, 2D printed structures such as triangular, square, or sine waves, serpentine arcs, horseshoe patterns, or spirals provide geometric length greater than the physical size of the printed pattern.[48,49] This enables physical changes such as twisting, extension, or rotation as they release their geometric length in response to increased physical elongation.[50,51] Based on this concept, elaborate fractal inspired constructs including lines, loops, and branch like geometries have been considered, of which Peano curves[52] show great promise for exploitation in future developments.[53] During either the fabrication process, or application of the device, in-surface or out of plane global in local buckling can impart physical damage to printed features.[54] In response to this, finite element analysis simulation methods have arisen to study formation of fatigue cracks in 2D interconnect features caused by buckling, assisting the optimization of geometric design for maximizing mechanical durability of interconnect features.[55]

In addition to the geometry of printed features, the formulation of printed materials may be controlled in order to minimize the breakdown of printed features resulting from mechanical deformations. For example, it is known that the addition of silver nanowires to silver nanoparticle ink can enable the subsequent structures to tolerate a greater degree of tensile bending, by forming electrically conductive bridging pathways across cracks formed between silver nanoparticles due to mechanical stress.[56] However, high aspect ratio materials can be larger than spherical nanoparticle ink components, posing practical challenges for printing technology, for instance by clogging of inkjet nozzles.[57] This motivates the development of stretchable materials by engineering their materials, structure, or a combination of these as detailed in a recent review article.[58]

New methods for improving mechanical durability of printed interconnects are evolving. For example, a recent report[59] describes how fused filament fabrication can be used to generate structures which support screen-printed conductive features by directing mechanical stress away from the interconnects' weak regions, improving the average maximum elongation of the interconnects by 27%.

TPU is a material with appealing mechanical properties (e.g. $E = 3.6$–88.8 MPa[29]) as a substrate for stretchable electronics. Via holes through stretchable substrates facilitates design and fabrication of double-sided printed circuits, enabling printing of more complex layouts with efficient use of materials. A full R2R process was recently developed for fabrication of electrically conductive silver serpentine tracks printed on TPU with through-substrate via interconnects.[60] This process investigated the performance of via holes formed by either R2R laser or die cutting TPU, in combination with R2R rotary screen-printing for patterning conductive silver tracks on both sides of TPU substrate and for filling of via holes with silver paste. The developed process was exploited for demonstrating electrocardiography (ECG) electrode structures depicted in Fig. 2 and could find further applications such as energy harvesting and storage.[61]

PDMS is a highly stretchable ($E \leqslant 3$ MPa[6,30,31]) elastomeric material that is widely used in research and development of microfluidic devices and these have recently been demonstrated to be fabricated by high volume R2R process.[63] Printing of conductive interconnect features on PDMS is challenging due to the low PDMS surface energy of 20–30 mJ m^{-2} causing poor adhesion of deposited materials.[64] Ozone treatment is a useful approach for altering the surface energy of PDMS. Ozone treatment was applied to change the contact angle of water from 96.7° to 7.5° in regions defined by a shadow mask, enabling the patterning of a masking liquid that was employed as a print stamp for patterning of thermally evaporated metal.[65] However, this process restricts high throughput manufacture because the ozone treatment step requires an extensive duration followed by a subsequent reduced pressure evaporation that further extends the procedure time. Recently, PDMS has been demonstrated as a substrate for high throughput R2R rotary screen-printing of silver interconnects, as depicted in Fig. 2.[62] This process was

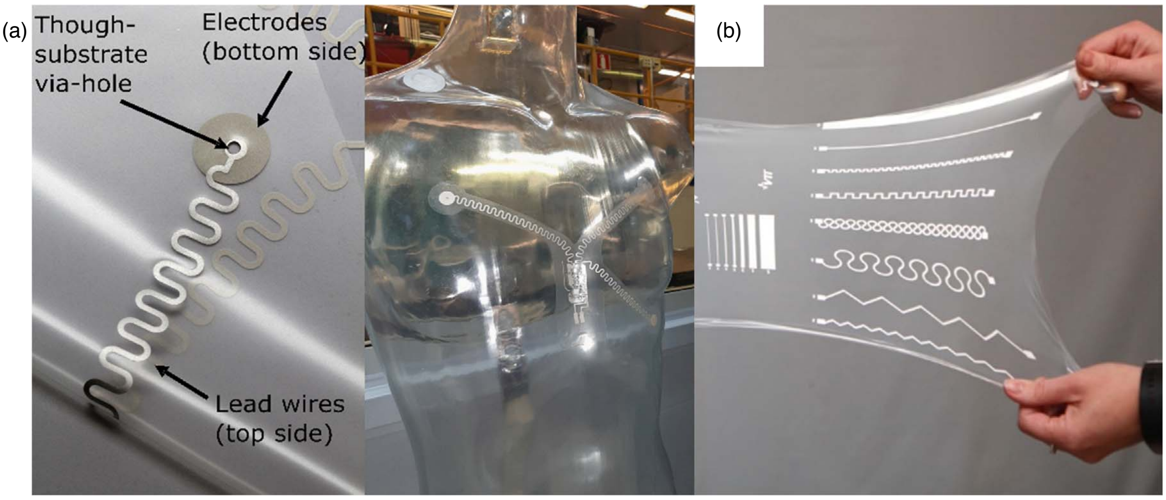

Fig. 2. (Color online) (a) Silver ECG electrode structures featuring double sided R2R printing on TPU linked through the substrate with R2R cut vias (2 mm hole diameter) and R2R filled via holes (reproduced from Ref. 60 under terms of the CC-BY license). (b) Stretched PDMS film with R2R-printed silver structures of varying geometry (reproduced from Ref. 62 under terms of the CC-BY license).

assisted by use of a non-stretchable PET carrier film to support the stretchable PDMS and careful control of the printing contact nip pressure to minimize deformations to the PDMS caused by contact with the screen during printing. The electrical conductivity of the printed features tolerated more than 100 cycles of repeated 20% strain. This strain durability was improved by a factor of two when the printed structures were mechanically supported by encapsulation with PDMS overlayer produced by R2R process.

2.4. Hybrid integration

R2R printed electronics such as those described in the previous section can be integrated with high-performance, mostly silicon-based microelectronics and other conventional rigid components to enable greater device performance than is currently possible using purely R2R printed components alone. These hybrid devices can be fabricated at high volume by pick and place assembly equipment in stop-and-go processing by R2R, sheet-to-sheet (S2S), or combining R2R and S2S methods.

This approach was used to realize a personal activity meter[66] composed of R2R-printed backplane and co-planar electrochromic display, with pick and place assembled accelerometer, microcontroller and passive components. The resulting structure was then supported by an injection-molded structure. Scalability of the fabrication process was demonstrated by manufacturing 100 complete units of the activity meter device.

Hybrid device architecture is particularly advantageous when integrating conventional components with a stretchable substrate. This was recently demonstrated in a stretchable circuit board formed from copper interconnects which tolerated soldering and was demonstrated as a wearable pressure monitor.[67] The resistance of the produced copper circuit wires only increased by around 20.6% under applied tensile strain of 80%. Unfortunately, the multi-step photolithography process poses limitations for high throughput manufacture. Another recent example of a hybrid device is the wireless elastic ECG system shown in Fig. 3, which is formed by scalable S2S screen printing of electrically conductive features on TPU, followed by component assembly via thermo compression using anisotropic conductive adhesive without any rigid or flexible interposer.[68] However, mechanical mismatch at the interface of soft and stiffened regions led to formation of cracks in the printed conductive features. This highlights the importance of reliability testing for flexible and stretchable electronic devices, which is discussed in the following section.

2.5. Reliability

Applications related to physiological monitoring in healthcare demand the utmost dependability from electronic devices, because it can literally be a matter of life or death. Reliability is a crucial aspect of all electronic devices, not only those applied in the healthcare sector, particularly where high volume manufacturing is performed and where devices are subjected to mechanical deformations such as stretching, bending, or torsion. Reliability is of particular concern in flexible and especially stretchable electronics, where reliability design and testing must be done in new ways compared to the industrial standard rigid FR4, or flexible PI substrates with soldering process. Use of stretchable substrate and conductive adhesives causes different failure modes that require new types of testing methods and models for estimation of device lifetime.

Conductive features printed on flexible or stretchable substrates are an important case for reliability studies. In these cases, failure commonly occurs due to slipping, delamination, or cracking caused by mismatch in the mechanical properties of the substrate and printed material.[69] Robustness of devices possessing such features is particularly challenged when materials are deposited on both sides of the substrate and connected with through substrate vias. Recently, such an architecture was challenged by bending reliability studies performed on laser cut and screen-print filled vias through 125 μm thick PET foil substrate.[70] The study revealed that a more viscous silver nanoparticle ink effectively fills the vias with 100% yield. Furthermore, 10 mm radius bending tests providing no evidence of via specific breakdown after as many as 30 000 cycles. However, increased electrical resistance was observed during bending tests, which could be explained by the formation of fractures between nanoparticles as described by

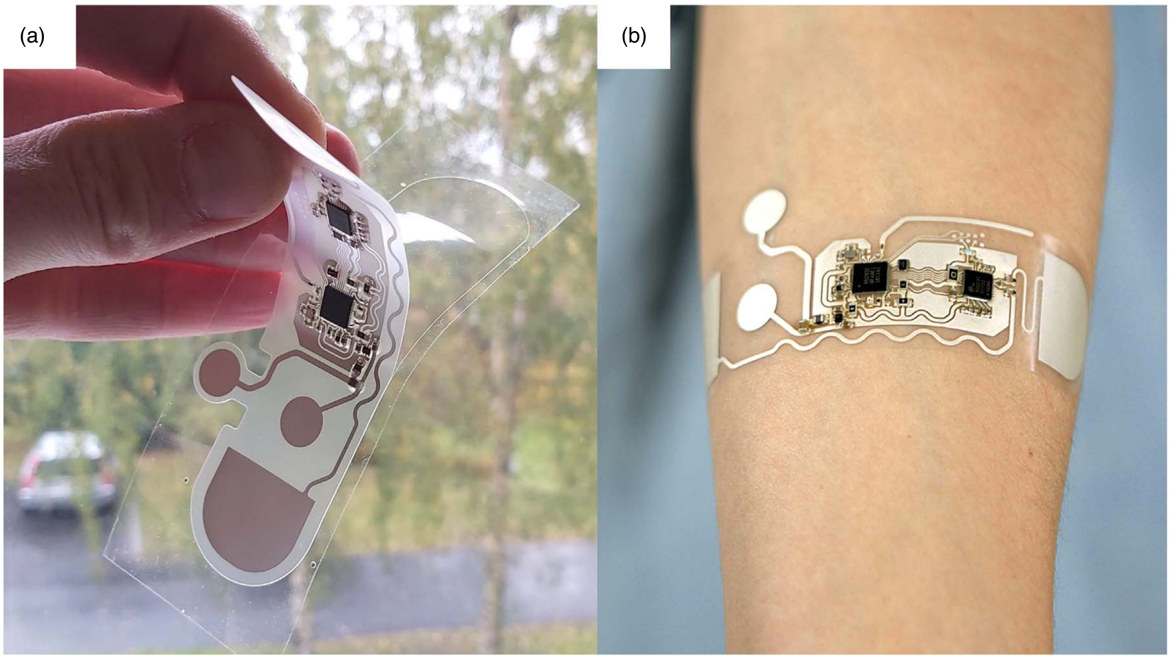

Fig. 3. (Color online) Hybrid integrated electronics realized in an ECG system on elastic TPU substrate[68] (a) being removed from carrier PET foil backing, (b) mounting on forearm reveals how well the device conforms to the body. Images courtesy of VTT Technical Research Centre of Finland Ltd.

Eq. (3) above. The vias were demonstrated as components of a flexible multilayer energy module with supercapacitor energy storage and organic solar cell energy harvesting functionality.

In another performance test of vias through TPU substrate, 100 cycles of stretching by 20% was performed.[60] It was observed that interconnections with a via hole diameter 1 or 2 mm tolerated the stretching tests, whereas those with 3 and 10 mm suffered reduced electrical conductivity across the interconnect. This could plausibly result from fractures formed in the large inflexible regions of nanoparticle material. The study confirmed that only the via sidewalls required ink coverage to enable proper interconnection between conductive features on both sides of the substrate. The developed R2R fabrication process delivered 100% yield of working vias.

Investigating the reliability of electronic devices under bending or stretching deformations is important. However, conformal and epidermal electronics attached to skin are also subjected to stress induced by twisting. This was considered in a study on the impact of torsional bending on PET supporting R2R screen-printed silver tracks.[71] Samples were twisted by 180° both clockwise and counterclockwise, while measuring four-point resistance and investigating heat patterns with thermography. The tests revealed that length to width ratio of the substrate drastically influenced the sample reliability, where samples with a length to width ratio below three experienced greater magnitude of stress. The study concluded that the reliability of printed conductive features could be optimized by electronics layout design. In this case, the test failure criteria was defined according to IPC-9701, whereby if the resistance of a sample increases by 20% or more from the initial value for six or more consecutive readings then the sample is classed as failed. Such pass/fail criteria are important for defining values applied in mass manufacture of electronic devices, to ensure compliance with quality assurance.

To enable integration with wearable devices such as textiles or other clothing, printed conductive structures must tolerate cleaning procedures applied to the carrier materials, for instance washing. To investigate this, a study was performed by attaching R2R-printed electrodes printed on TPU to stretchable fabric waist belts and then subjecting them to cleaning cycles with washing powder in a household style washing machine.[72] This process was understandably destructive to the printed structures, particularly those with smaller printed features. The washing process resulted in increased surface roughness and cracking within the bulk of the printed material, along with apparent decrease in silver and increase in carbon content. A key finding from the testing was that greatest reliability was provided by electrodes formed from precursor inks with particle size smaller than around eight μm. The authors postulate that larger particles are more prone to flaking off the sample, and/or forming larger voids as they are removed by the washing process. Furthermore, the printed silver tracks were made more robust by coverage with a R2R-printed protective carbon overlayer.[73]

Computer modeling is a useful tool for assessing reliability of electronic devices and can even be applied to tune manufacturing processes. For example, in the above-mentioned personal activity meter case,[66] modeling of fluid dynamics and numerical heat transfer revealed that shear stress and high filling pressure during injection molding, caused device failure. In addition to computer modeling, stability studies were performed on the devices. A series of devices was exposed to elevated temperature and humidity according to JESD-22 A101 standard Steady State Temperature Humidity Bias Life Test, with over molding process appearing to reduce degradation, plausibly by acting as a moisture barrier, preventing exposure of bare electronics to high humidity. A further stability test performed cyclic bending of samples around a 15 mm radius for 1000 cycles, with no observed failure in the electronics. However, the display part of the devices experienced damage, which the authors suggest could be rectified by improved mechanical design.

Reliability issues with hybrid electronics can occur due to mechanical mismatch between soft and rigid components.74) This occurred in the earlier mentioned elastic ECG system,68) which is another case where computer modeling was employed for reliability assessment. Finite element modeling (FEM) was used to complement experimental testing of device performance under tensile load. FEM is especially helpful in complex electrical systems, where a high density of active and passive components are mounted on a stretchable carrier substrate. In such cases, visual inspection methods are insufficient for identifying failure points. Particularly if the failure points can be hidden, or not immediately obvious when the substrate is in relaxed position with no strain or elongation. Moreover, in-advance FEM analysis could spot potential weak points of the printed circuit layout, assisting with prefabrication reliability assessments. Durability testing of the devices revealed that they remain operational after hundreds of deformations cycles with uniaxial strain at 5% and 10% elongation. However, the device stopped collecting ECG data at the peak (10%) of elongation, then resumed operation once relaxed from strain. This can be explained by cracks observed at the interface where between stiff and soft regions of the device. Elongation of the device generates cracks in the interconnecting features, creating a barrier to electron flow. As shown in Fig. 4, these failure point locations were supported by FEM simulations, with edges of high deformation regions in agreement with the observed locations of high crack density.

A recent study deeply investigates mechanical failure mechanisms in a hybrid temperature logging device formed by S2S process on TPU, with sequential printing of silver, insulator, silver cross over, then thermode chip bonding.75) The report highlights the impact of conductive adhesive mechanical properties, with air voids noted as key a contributor to device reliability failure. Nevertheless, samples fabricated with an optimum combination of conductive adhesive and conductive ink did satisfy the reliability target of 5000 strain cycles of 20% elongation.

Acceptance criteria for reliability testing of electronic devices is chiefly governed by the use case for the device, with differing standards defined for specific applications such as healthcare, military, aerospace, and automotive cases. However, the testing strategies described in this section can be applied to many forms of flexible and stretchable electronics to improve and enhance device design, architecture, and yield. Particularly when fabricated by high throughput methods.

2.6. Sustainability

Manufacture of stretchable electronics can offer lower consumption of raw materials and decreased energy consumption when compared with processes for fabrication of traditional rigid devices.76) However, as described in previous sections, flexible and stretchable electronic devices are typically fabricated on synthetic polymer substrates such as PET, TPU, or PDMS, with metals and other components that are not derived from sustainable sources, easily recyclable, or degradable at the end of a device's lifetime. A more eco-conscious approach to device fabrication would include incorporation of more sustainable substrate materials,77) and replacing conductive silver inks with alternatives such as carbon or natural biopolymers.78) Paper has recently been reported as a substrate for R2R fabrication of a smart label with electrochromic display, near field communication, and circuitry.79) However, properties such as high moisture absorbance, low tear resistance, and poor stretchability restrict paper as a substrate for many conformal wearable applications.

One solution for a more sustainable substrate than pure synthetic polymers, is to form a composite from natural substances such as cellulose.80) For example, a composite composed of nanocellulose and polyurethane, where physical properties such as the Young's modulus can be tuned by adjusting the concentration of nanocellulose.45) This material was prepared by high volume pilot line processing, and then formed into a hybrid device for temperature measurement, with printed silver tracks connecting surface mount components. Cellulose based films can be made highly transparent (90% transparency per 100 μm at 550 nm wavelength) and able to elongate up to 233%.81) Furthermore, replacing traditional synthetic polymers with greener alternatives such as polyvinylpyrrolidone (PVP)82) shows promise for the generation of biodegradable stretchable electronics.83)

Further development of materials such as these are expected to shift stretchable electronics devices to integration of more environmentally friendly materials and components, towards a more sustainable future.84)

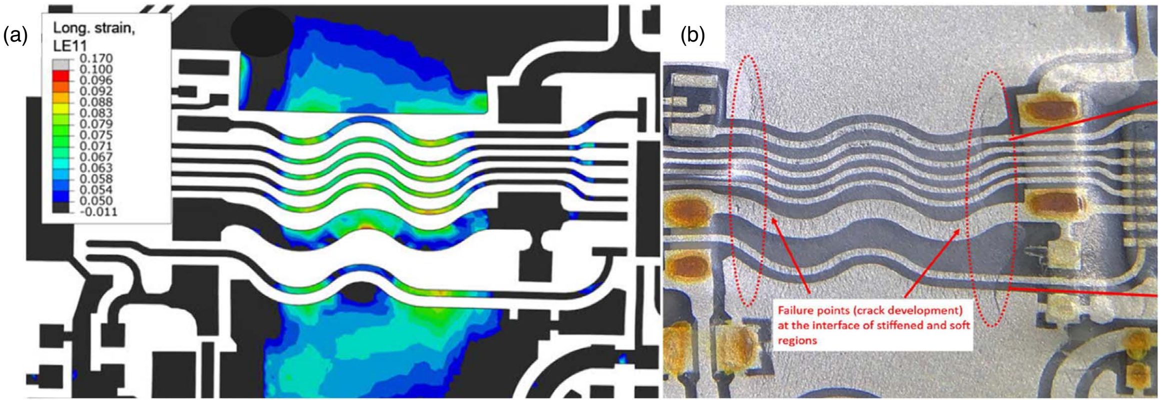

Fig. 4. (Color online) Reliability test findings from an elastic ECG system, with identification of failure point locations in agreement between (a) FEM strain simulation for the distribution of longitudinal deformations, and (b) visual inspection (reproduced from Ref. 68 under terms of the CC-BY license).

3. Summary and outlook

Wearable systems based on flexible and stretchable electronics platforms enable vast applications including sports, military, and healthcare. Evolving manufacturing strategies can facilitate high volume device production required for large population research and development studies, or commercialization. However, reliability testing of stretchable electronic devices demands dynamic procedures, which typically require tailoring for a given case. Further developments in scalable fabrication processes and reliability testing of hybrid integrated stretchable electronics devices is required to realize high throughput manufacture of robust devices with high inter-device uniformity. Moreover, such production of large volumes of electronic devices comes at an environmental cost. This motivates a shift towards integration of components from sustainable origin and having eco-friendly possibilities such as degradability or recycling at the end of the device's lifetime.

Conflict of interest

The authors declare no conflict of interest.

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