

Transient Electronics as Sustainable Systems: From Fundamentals to Applications

Reihaneh Jamshidi,* Mehrnoosh Taghavimehr, Yuanfen Chen, Nicole Hashemi, and Reza Montazami

The unique attribute of transient technology is that it promotes the potential for the design and implementation of sustainable systems through their capability to fully or partially disintegrate after a predefined period of stable operation. Transient electronics have a wide range of potential applications as biomedical implants, environmental sensors, and hardware-secured devices. Controlled disintegration of such systems without the need for harsh solvents is a step toward realizing green and sustainable electronics. In this short review, recent progress in the development of transient electronics is studied. First, an overview of the transient materials, both the substrate and electronic component, is described. Second, the mechanisms under which transiency occurs, including aqueous dissolution and thermal degradation, are reported. Third, manufacturing techniques for the fabrication of transient electronics are reviewed. And last, various transient electronic devices and their applications are discussed.

unique attribute of transient electronics is that they are designed to operate over a typically short and predefined duration of time and disintegrate fully or partially when no longer needed.

This concept can be applied to a number of different systems, including implantable biomedical devices,^[1,2] environmental sensors,^[3,4] and hardware security,^[5,6] to name a few examples. Transient implantable biomedical devices could be designed to degrade within the body after a predefined period of reliable operation; this will eliminate the need for secondary surgery needed to extract the device. Transient environmental sensors made of environmentally friendly (green) and degradable polymers could be utilized to collect various types of data such as

1. Introduction

Transient electronics is an emerging class of functional electronic devices that have been at the focus of a substantial number of research efforts in the materials science community. Unlike conventional electronic devices that are designed to remain functional and stable over extended periods, the

humidity and pressure, then be absorbed into the environment, minimizing bulk waste that is harmful to wildlife, such as birds and fish. And last, transient hardware-secured devices could undergo disintegration, making sensitive information irretrievable upon degradation.


Research in transient electronics started with the integration of conventional electronic components on a degradable substrate and was followed by the integration of partially transient electronic components and a few fully degradable components.^[7–9] The most recent form of transient electronics, however, is fully transient.^[10–14] To date, researchers have successfully synthesized and designed material systems and transiency mechanisms that allow electronic devices with functionality and performance level of the conventional counterparts, and yet capable of undergoing disintegration once needed.

This short review will report on the materials used in transient electronics, mechanisms that facilitate transiency, manufacturing techniques of this class of electronics, and transient electronic devices developed so far and their potential applications.

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2. Transient Materials

Structural components of electronics, in general, consist of a substrate that acts as the mechanical support and electronic components that are responsible for the functionality of the system. In the case of transient electronics, all the constituents must be capable of dissolution or disintegration to facilitate

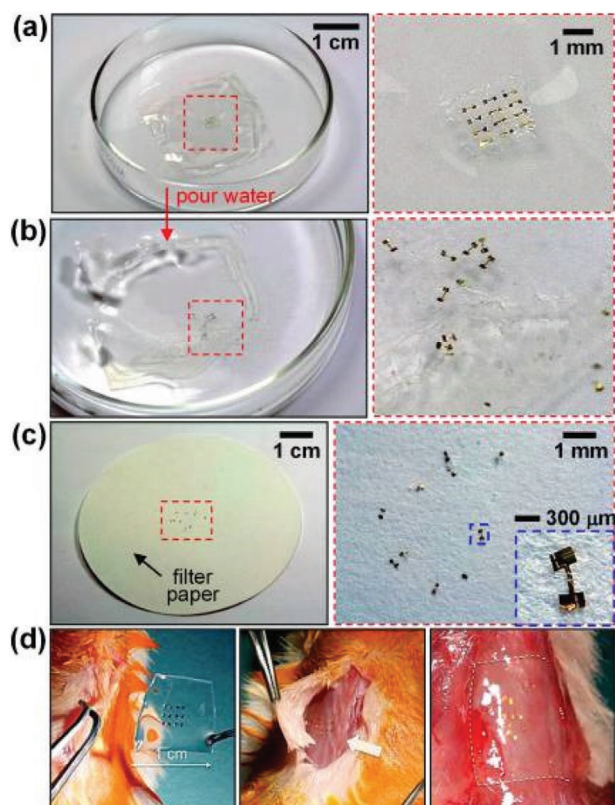


Figure 1. Sequential images of the water dissolution of a system of silicon electronics on silk (left) with magnified views (right), a) start, and b) after 3 min. c) Image of devices recovered on filter paper after complete dissolution of the silk (left) with magnified view (right). d) Procedure and result of the animal toxicity test: image before (left) and shortly after (center) and two weeks after (right) implantation. Reproduced with permission.^[16] Copyright 2020, AIP Publishing.

the full transiency of the device. Below is an overview of the advancements in transient substrate materials and transient electronic components.

2.1. Substrates

The role of substrate in transient electronics is twofold. One role is to provide mechanical support, and the other is that the transiency attribute of the substrate can facilitate or control the disintegration mechanism of the electronic components. Montazami et al. have reported on the disintegration of insoluble electronic components in water through the swelling attributes of a polyvinyl alcohol (PVA)-based substrate.^[15]

To our best recollection, the first bioresorbable substrate reported for transient electronics is silk by Kim et al. in 2009.^[16] In their study, a largely bioresorbable system for implantable biomedical devices was fabricated on a 25 μm thick silk substrate. **Figure 1** is the illustration of the dissolution of a device on a 25 μm thick silk substrate. The complete dissolution of the silk substrate occurred in 3 min (Figure 1a,b). Figure 1c shows the recovery of the electronic components on a filter paper after the substrate has disintegrated. Following this study, a variety of transient electronics based on silk substrates were reported.^[7,11,17–19] Silk has been attractive as a substrate for transient electronics due

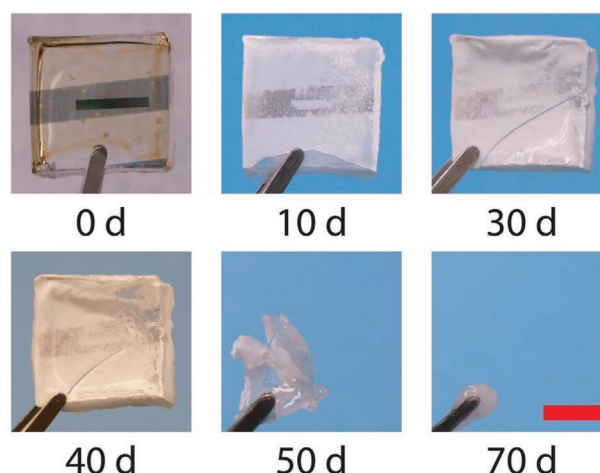


Figure 2. Photographs from representative devices at various stages of the degradation. Devices also transitioned from being initially optically transparent (0 days) to opaque within 10 days. Scale bar represents 5 mm for all panels. Reproduced with permission.^[9] Copyright 2021, Wiley.

to its robust mechanical properties and controllable degradation rate facilitated by enzymatic mechanism.^[20]

Another class of bioresorbable substrates for transient electronics is thermoplastic polymers. Bettinger et al. have reported on the application of poly(L-lactide-co-glycolide) (PLGA) as a degradable substrate for organic thin-film transistors.^[9] **Figure 2** demonstrates the degradation stages of the electronic device fabricated on PLGA substrate in water. The device remained relatively intact for 30 days. At 40 days, a noticeable mass loss is observed, followed by the total loss of structural integrity at approximately 70 days. In another study, PLGA, polylactic acid (PLA), and polycaprolactone (PCL) have been developed as substrates for manufacturing transient electronic circuits.^[13] Prior to transient electronics, PLGA and PLA were applied for controlled degradation drug delivery due to their biodegradability.^[13,19,21] Another promising candidate material to be used as a substrate for transient electronics is PVA.^[22,23] Acar et al. have successfully designed PVA substrates with a controlled dissolution rate in water using sucrose and gelatin as fillers. While sucrose proved to accelerate the PVA's dissolution rate in water, gelatin decelerated the dissolution mechanism; together, providing the means for a controlled and tunable degradation.^[23]

In addition to biodegradable thermoplastics, biodegradable elastomers are reported as soft substrates for flexible/stretchable transient electronics. Kim et al. have employed poly(glycerol-co-sebacate) (PGS) to develop electronic power sources that could serve for the stimulation of bodily tissues.^[24] Another example is electrospun sheets of poly(caprolactone)-poly(glycerol sebacate) (PGS-PCL), utilized to develop elastic electronics such as strain gages, biocompatible heaters, and temperature sensors.^[25] Presented in **Figure 3** are the images of the fabricated electronic device on PGS-PCL sheets, before and after the complete degradation of the substrate in a solution of 0.5 M NaOH, after 30 days. Hwang et al. have also reported transient electronic devices on a poly(1,8-octanediol-cocitrate) (POC) elastomeric substrate with the reversible stretchability of up to 30%.^[26]

Thin metal foils such as Mo, Fe, W, and Zn foils with a thickness of 5–10 μm , have also been reported as substrate materials for transient electronics.^[27] Thin metal foils are favorable for

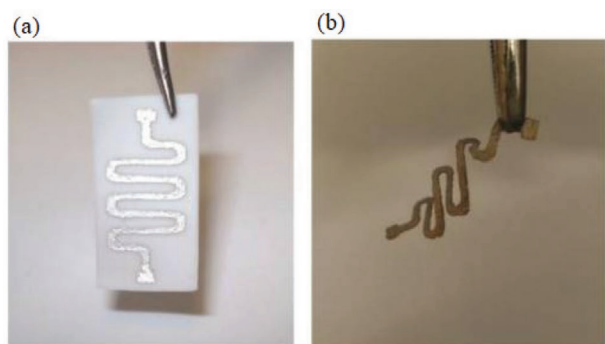


Figure 3. Fabricated device on PGS-PCL a) before and b) after the degradation of the substrate in 30 days. Reproduced with permission.^[25] Copyright 2021, Wiley.

applications where high-temperature stability is required or the absence of swelling is preferred. Considering electrical conductivity of the metal foils, ultra-thin transient insulating layers are needed to maintain circuit functionality and prevent shorting. Presented in **Figure 4** are sequential images of dissolution for n-channel metal-oxide-semiconductor field-effect transistors (MOSFETs) in phosphate buffer solution (PBS) at pH 7.4 and 90 °C. The section immersed in water is fully dissolved after 25 days.

Other biodegradable substrates include natural materials such as chitosan, rice paper, cheese, charcoal, and seaweed.^[28–30] An interesting example is a chitosan and rice paper substrate used for the fabrication of a transient switching memory device. **Figure 5a** demonstrates an electronic device consisting of Mg electrodes on a chitosan substrate. **Figure 5b–d** shows gradual degradation of the chitosan substrate as well as the Mg electrodes upon exposure to DI water. Degradation proceeded until complete decomposition.

Besides water-soluble substrates, polymers that decompose when subjected to light or heat have been studied and reported as well. Moore's group^[31,32] presented a metastable polymer, cyclic poly(phthalaldehyde) (cPPA), which can be self-depolymerized back into monomers when triggered by heat or light. They first reported a Ultraviolet (UV) light-triggered transient substrate by incorporating a photo-acid generator (PAG) into the cPPA polymer matrix. In a later study,^[33] they presented a heat-triggered transient electronic device with a double layer substrate: a methanesulfonic acid/wax layer would release acid when heated, and a cPPA layer would disintegrate by the acid.

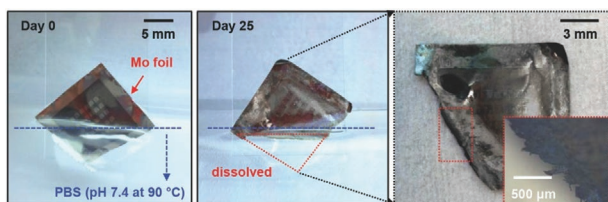


Figure 4. Sequential images collected at various stages of dissolution of a transistor array on a Mo foil ($\approx 5 \mu\text{m}$) partially immersed in phosphate buffer solution (PBS, pH 7.4) at 90 °C. The device in its initial state (left) and partially dissolved after 25 days (middle). Magnified (right) and microscope (inset) images show full dissolution in immersed areas and partial degradation of Mg electrodes by vapor in an adjacent region. Reproduced with permission.^[27] Copyright 2021, Wiley.

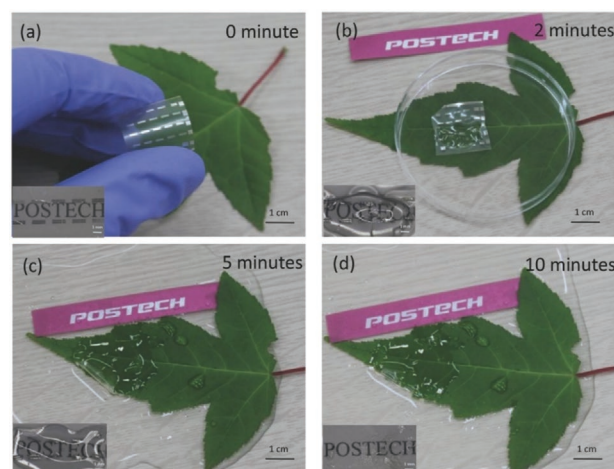


Figure 5. Biodegradable and decomposable devices made of chitosan as the substrate with coplanar Mg electrodes. Reproduced with permission.^[28] Copyright 2021, Wiley.

2.2. Electronic Components

Electronic components determine the functionality of electronic devices. In a typical electronic device, electronic components comprise four major types: semiconductors, electrodes, interlayer connectors, and dielectrics. In the case of transient electronics, the transiency requirement limits the number of possible materials that can be selected and used as constituents of the functional components. As a result, the investigation for transient electronic components with functionality comparable to that of the conventional counterparts is still ongoing.

Semiconductors are key components in transistors and diodes. Transistors in turn are building blocks of almost any electronic circuit, making semiconductors essential elements of computers, cellphones, and other memory and logic devices. To our best knowledge, Rogers's group, for the first time, reported a physically transient form of silicon nanomembrane (30–300 nm) and applied them as semiconductors for transient electronics.^[17,34–36] Additionally, they investigated other transient semiconducting materials, including amorphous silicon, polycrystalline silicon, silicon-germanium, germanium,^[37] and zinc oxide (ZnO).^[19] **Figure 6** shows the dissolution stages of a meandering trace of ZnO (200 nm) in deionized water at room temperature, which was completed after 15 h. The dissolution behavior of semiconductors such as polycrystalline silicon and

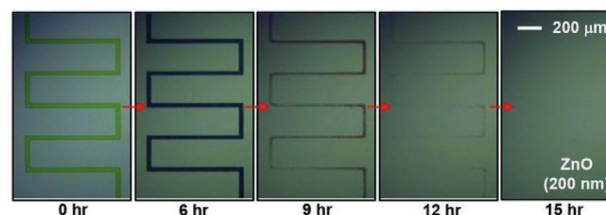


Figure 6. A series of optical microscope images collected at various times during dissolution of a meandering trace of ZnO (200 nm) immersed in deionized water at room temperature. Reproduced with permission.^[19] Copyright 2021, Wiley.

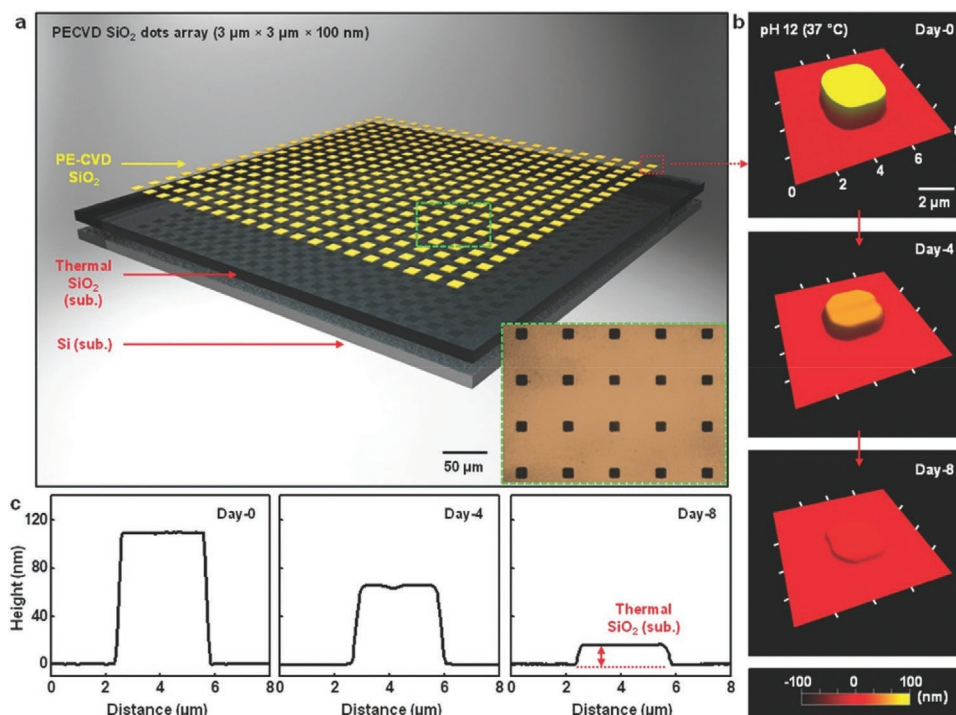


Figure 7. a) Schematic illustration of an array of square pads (3 μm × 3 μm × 100 nm) of PECVD SiO₂ deposited at 350 °C on a thermally grown oxide on a silicon wafer, with inset optical micrograph. b) AFM topographical images and c) profiles of a representative pad at different stages of hydrolysis in buffer solution (pH 12) at physiological temperature (37 °C). Reproduced with permission.^[38] Copyright 2021, Wiley.

silicon-germanium reported by Kang et al. suggests a correlation between the transiency rate, temperature, and pH of the aqueous solvent. The transiency rate proved faster at physiological temperature (37 °C) compared to room temperature. At a constant temperature, it was faster in an alkaline medium compared to one at the neutral pH.^[37]

Another key component in electronics is interlayer or gate dielectric. Silicon oxide (SiO₂) and silicon nitride (Si₃N₄) have been reported to have excellent dielectric properties and be capable of controlled dissolution, therefore applicable for transient electronics.^[38] Presented in Figure 7a is the schematic illustration of a plasma-enhanced chemical vapor deposition (PECVD) SiO₂ layer deposited at 350 °C on a thermally grown oxide layer on a silicon wafer. Figure 7b illustrates the dissolution stages of a 100 nm thick square pad in an aqueous buffer solution (pH 12) at 37 °C with the thickness profile at each stage presented in Figure 7c. Similar to the semiconductors, the dissolution rate of SiO₂ at a constant temperature (37 °C) proved to be faster in an alkaline medium compared to one at the neutral pH, and there exists a linear correlation between the pH and the dissolution rate at 37 °C.^[38] Other materials that have demonstrated applicability as gate or interlayer dielectric in transient electronics include magnesium oxide (MgO),^[6,39] magnesium difluoride (MgF₂),^[40] silicate spin-on-glass (SOG),^[27] and egg albumen.^[41]

Electrodes and interlayer connectors are also essential components of electronics. Water-soluble metals such as Mg, Zn, W, Fe, and Mo have been studied for their application as electrodes or interlayer electrodes in transient electronics.^[17,24,29,42,43] Yin et al. studied and compared the dissolution of thin metal films

in DI water and found a faster dissolution rate for Mg and Zn in comparison to W and Mo.^[35] Dissolution progress of sputter-deposited Mo in DI water is demonstrated in Figure 8. The rate for the dissolution of Mo is specified to be approximately $3 \times 10^{-4} \frac{\mu\text{m}}{\text{h}}$. Colloidal metal inks have also been investigated for their application as electrodes in transient electronics. Montazami's group has explored the use of silver microparticles as electrodes in transient electronics.^[15,44] In their studies, the transiency of the electrode layer was facilitated by swelling of the PVA substrate in an aqueous solvent, followed by disintegration and redispersion of the electrode into the dissolution medium.

3. Transiency Mechanisms

The degradation of transient materials can be controlled over time using several stimuli,^[45] such as pH, temperature, light, mechanical force, and exposure to different solvents. In the following sections, some of the triggering mechanisms will be discussed.

3.1. Dissolution

Dissolution in an aqueous medium is the most common triggering mechanism for transient electronics.^[46–49] Fu et al. have reported a transient Li-ion battery with stable performance for repeatable use and the capability to completely dissolve in water within minutes. The components of this transient battery are V₂O₅ cathode, lithium metal anode, PVP separator, and sodium

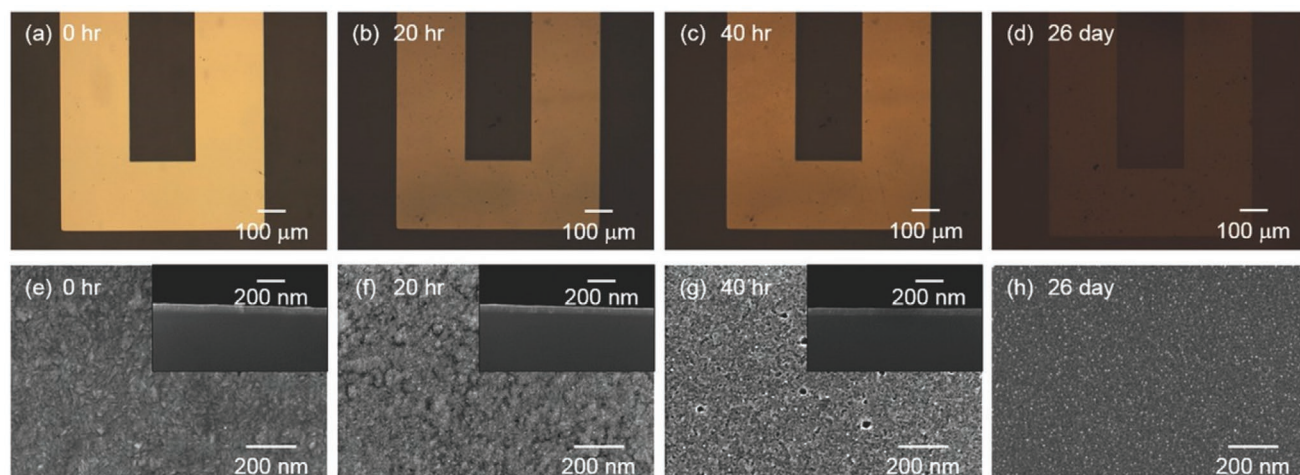


Figure 8. Evolution of microstructure and surface chemistry associated with dissolution of Mo in DI water. a–d) optical images; e–h) SEM images with cross-sectional views in the insets. Reproduced with permission.^[35] Copyright 2021, Wiley.

alginate for the encasement. A schematic of the triggering mechanism and chemical reactions responsible for the dissolution is demonstrated in Figure 9a,b.^[48]

Kang et al. investigated the dissolution behavior of amorphous silicon (a-Si) solar cells. These cells utilized ZnO with Al dopant as the transparent conductive oxide (TCO), and Mg was

applied as bottom and top electrodes. The conducting layers of Mg and ZnO dissolved within several hours, and further diffusion of the solution into the multilayer stack led to the disintegration of hydrogenated amorphous silicon (a-Si:H) films within days (Figure 10).^[49]

Chen et al. have introduced a transient Li-ion battery that achieved transiency through a hybrid approach: dissolution of the soluble components and disintegration of insoluble ones. In this study, PVA was used as the substrate and as a binder for the cathode and anode active materials. Hydration of PVA in water generated a swelling force that led to the disintegration of insoluble components of the battery, resulting in the redispersion of insoluble nano/micro-materials in the liquid medium. To further understand swelling-induced transiency, finite element models were developed and used to study and analyze interfacial stress and fracture for typical electrodes.^[50]

The dissolution mechanism can be regulated by applying encapsulation layers such as PCL, PVA, PLA, PLGA, and polyanhydride.^[47,51] The encapsulation layer can be adopted to delay and/or slow down the transiency of the electronic components and thus increase their operation time. Li et al. reported biodegradable capacitors (BC) with tunable operation time from days to weeks by using PVA and PLA encapsulations along the edges of the device.^[47] The disadvantage of this approach is the insulation of the device from its environment, which may be a limiting factor for specific applications such as humidity sensors or biosensors.

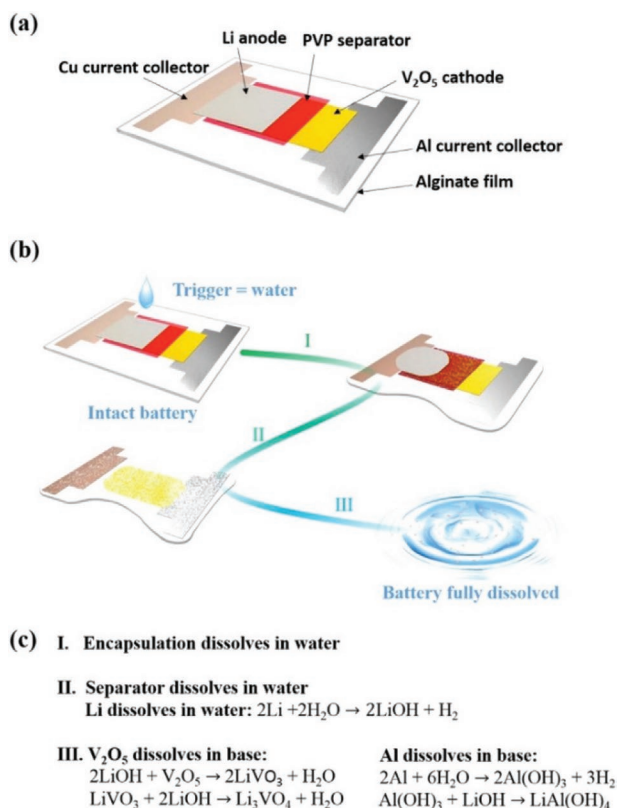


Figure 9. a) Schematic representation of the transient battery structure. b) Schematic process of triggered battery dissolution. c) Chemical reactions responsible for the dissolution of each battery component. Reproduced with permission.^[48] Copyright 2020, ACS Publications.

3.2. Photo Degradation

While most studies have focused on transiency through an aqueous medium, the use of other transiency mechanisms can extend applications of transient electronics in different environments. Presented by Hernandez et al., UV light could result in rapid depolymerization of low ceiling temperature cPPA by triggering a PAG additive. The generated acid also leads to degradation of the electronic components and, thus, the whole device.^[31]

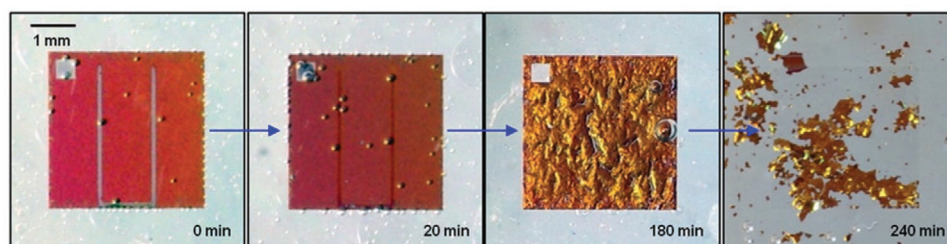


Figure 10. Optical images at various stages of dissolution of a thin a-Si:H solar cell. The conducting layers of Mg and ZnO dissolve over several hours, followed by complete dissolution of a-Si films within days. Reproduced with permission.^[49] Copyright 2020, ACS Publications.

Chen et al. have demonstrated that light-triggered dissociation of cyanide from potassium ferrocyanide- $K_4[Fe(CN)_6]$ can be used as a means to completely dissolve a gold electrode within several minutes.^[52] **Figure 11** demonstrates the dissolution progress as a function of exposure time.

3.3. Thermal Degradation

Degradation of electronics by the environmental stimulus is of great interest.^[34,49] Thermally triggered electronics can offer an advantageous destructive method, which is not limited to the dissolution mechanisms of the substrate and electronic components.

Gao et al. used electrospun PCL nanofibrous polymer as the flexible substrate of ultra-thin Si photodetectors. Heating the PCL film above its melting temperature caused significant shrinkage, followed by mechanical destruction of the electronic components. The shrinkage of nanofibers was due to the relaxation of the PCL chains.^[53]

In another study, polyoxymethylene (POM) without end-capping was introduced as a novel thermally unstable material for transient electronics.^[54] As presented in **Figure 12**, upon

exposure to heat (180 °C), the POM film depolymerized, which caused the disintegration of the Cr/Au/SiO₂/Cu device.

In some cases, multiple triggers can be applied simultaneously in order to achieve the transiency of an electronic device. Park et al. reported thermally triggered transient electronics, which are coated with wax containing acid microdroplets. Upon exposure to heat, the wax coating melts, which then results in acid release followed by the deconstruction of the Mg electrodes. Additionally, using the cPPA substrate enabled a faster degradation of the electronic device owing to the acidic depolymerization of cPPA.^[32]

Hernandez et al. presented the application of cPPA films doped with thermoacid generators (TAGs) that are triggered in response to heat. They found that adding 2 wt% TAG (with respect to cPPA) would lower the mass loss onset of cPPA by 22 °C.^[55] As shown in **Figure 13a,b**, the TAG incorporated in cPPA film is activated and releases acid upon exposure to heat. The released acid leads to cleavage of acetal bonds and depolymerizes cPPA into monomers, which evaporates at elevated temperatures.

4. Manufacturing Techniques

Transient materials are inherently unstable or are susceptible to instability. As a result of these constraints, the fabrication of transient electronic devices is a challenging process and very often requires creative and unorthodox approaches to manufacturing. The most common manufacturing technique for transient polymeric substrates is solution casting.^[11,14,24,27,35,42,56] Another manufacturing technique for a substrate is electrospinning, which has been employed for the fabrication of elastic and biodegradable fibrous polymeric substrates.^[1,25] This method has also been used for the fabrication of degradable membrane separators for a transient Li-ion battery.^[48]

Various methods are adopted for printing the electronic components onto a transient substrate. Screen printing is a commonly used method for the fabrication of electronic components.^[15,57] In this technique, a mask is designed and placed on top of the substrate, and the electronic component is then sprayed or doctor-bladed into the pattern in the form of thin layers. Digital printing is a relatively new technology where the printing design is controlled via software instead of a mask.^[58] Chen et al. have recently reported the application of electrohydrodynamic jet printing, which is a low-cost digital and drop-on-demand technique, for printing conductive conjugated polymer electrodes onto a transient substrate.^[59]

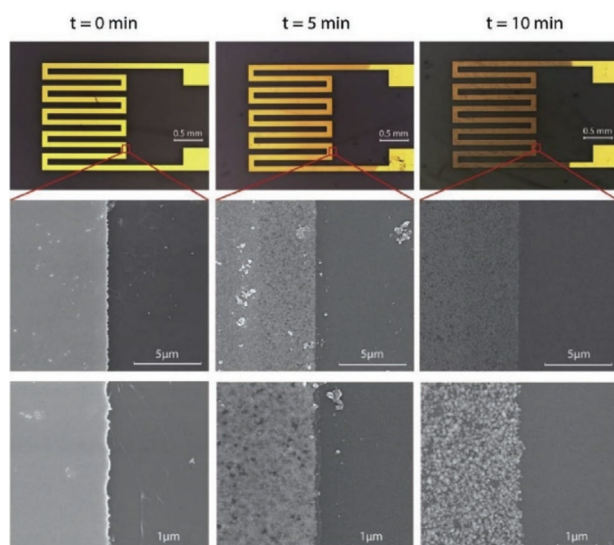


Figure 11. Light microscope and SEM pictures of the gold surface before, after 5, and after 10 min of illumination. Dissolution is progressing with increasing illumination time. Reproduced with permission.^[52] Copyright 2021, Elsevier.

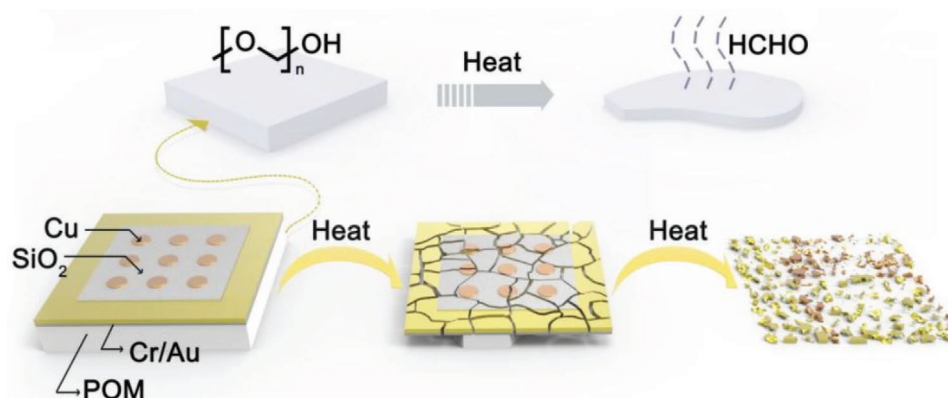


Figure 12. Thermally triggered process of POM/Cr/Au/SiO₂/Cu device. Reproduced with permission.^[54] Copyright 2020, Springer Nature.

Photolithography is another high-resolution method that is well known for the fabrication of semiconductors.^[34,49,60,61] Transient substrates, however, which are frequently polymeric materials, are sensitive to the high temperatures required by lithography (above 100 °C) and could not remain stable throughout the process. To accommodate different manufacturing techniques required for different constituents in transient electronics, a novel fabrication scheme called transfer printing is developed to integrate transient devices.^[31,62–64] In this technique, the active components are printed using conventional photolithography and then transferred onto the transient substrate by contact printing (such as picking up the printed features by PDMS stamp and placing them onto the desired location).^[64] **Figure 14** shows the fabrication process of a transient transistor starting with undercut etching of circuit components from a silicon on insulator (SOI) wafer, followed by transfer printing to a film of silk.^[65] Of course, materials-transient or conventional- used in this approach must be compatible with conventional photolithography techniques.

5. Applications and Devices

Transient electronics developed so far range from electronic elements to system-level platforms. Examples of electronic elements are field-effect transistors,^[7,10,11,18,19,62] complementary metal-oxide semiconductors (CMOS),^[9] logic circuits,^[62] and electronically instrumented stents.^[34] System-level devices can be categorized into three main application areas: biomedical

applications, environmental applications, and hardware security applications. Each category is discussed below in more detail.

5.1. Biomedical Applications

Transient electronics can benefit from biomedical implantable devices by eliminating the need for secondary surgeries for device extraction. In a study by Roger et al. a fully transient silicon-based implantable device was developed to deliver thermal therapy and was demonstrated in animal models. The device was composed of magnesium inductive coils integrated with resistive microheaters of silicon nanomembrane (Si NM) on silk substrate and packaging material. This device can assist with infection mitigation and localized pain relief by generating localized heating.^[62]

Kang et al. have reported an implantable silicon-based sensor capable of monitoring intracranial pressure and temperature. This functionality, which is essential for the treatment of brain injury, was developed by a materials system that is fully transient and resorbs within the body.^[66] **Figure 15a** is a schematic illustration of the transient pressure sensor. The pressure responses measured by this sensor agree quantitatively with those of clinically standard sensors (**Figure 15b**). Boutry et al. have also reported a transient pressure sensor for monitoring cardiovascular activities. The transient sensor demonstrated stable operation under bending radii down to 27 mm, which is sufficient for its purposed application.

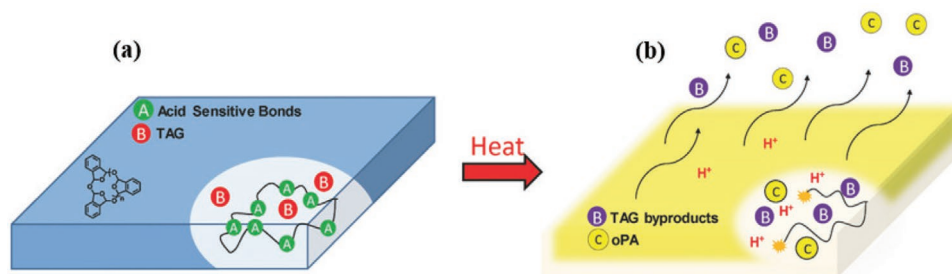


Figure 13. Thermally triggered acid-catalyzed cPPA depolymerization a) Thermoacid generator is blended and dispersed in cPPA film. b) Heating of the film produces acid. Reproduced with permission.^[55] Copyright 2021, Wiley.

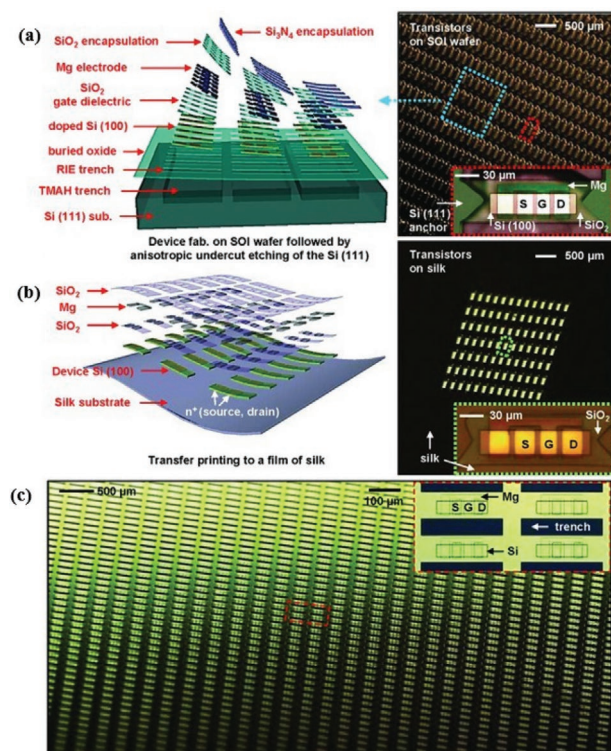


Figure 14. Fabrication of transient transistor. a) Schematic illustration and optical microscope images of devices after complete processing followed by anisotropic undercut etching of the SOI wafer substrate. b) Schematic illustration and image of these same devices after transfer printing to a film of silk. c) Optical image of a large area of n-channel MOSFETs, with microscope image of a representative set of devices in the inset. Reproduced with permission.^[65] Copyright 2021, Wiley.

Other examples of transient electronic devices with biomedical applications include transient pH and electrophysiological (EP) sensors,^[26] and transient hydration sensors for monitoring the wound healing process on the skin.^[13] Transient electronics for drug delivery applications have also been reported.^[1,2,67] Feiner et al. have developed an implantable scaffold for cardiac

tissue engineering, which is capable of monitoring tissue performance and stimulation of anti-inflammatory drug release.^[1]

5.2. Environmental Applications

Transient electronics can benefit the environment by minimizing electronic waste (e-waste). An example is a degradable temperature sensor that can be utilized for temperature measurement of hard-to-reach environments, and at last, get absorbed into their environment.^[4] Other examples are green batteries, compostable portable electronic devices, and light-emitting devices with the potential to reduce e-waste.^[3,13] **Figure 16** shows the dissolution stages of a transient alternating current electroluminescent (ACEL), composed of a sandwich structure of silver nanowires (Ag NWs)/phosphor-polyvinyl pyrrolidone(PVP)/Ag NWs, in DI water at room temperature. The transiency of the ACEL devices paves the way toward the mitigation of e-waste issues and the resultant environmental pollutants.^[3]

5.3. Security Applications

Transient electronics are deemed attractive for hardware-secured devices containing sensitive information that needs to be unrecoverable. While the transiency period for biomedical and environmental applications can be days or months, this period shall not exceed a few minutes for security purposes in transient hardware secured devices. Sun et al. have developed a transient threshold switching device based on MgO that can contribute to secure storage applications. The proposed materials system can degrade upon triggering by deionized water within 8 min at room temperature.^[6]

A transient switching memory device based on a natural organic polymer (chitosan) has also been developed, which is a suitable candidate for flexible memory devices.^[28] A schematic illustration and photograph of the chitosan-based resistive switching memory device are presented in **Figure 17a,b**. The resistive switching behavior

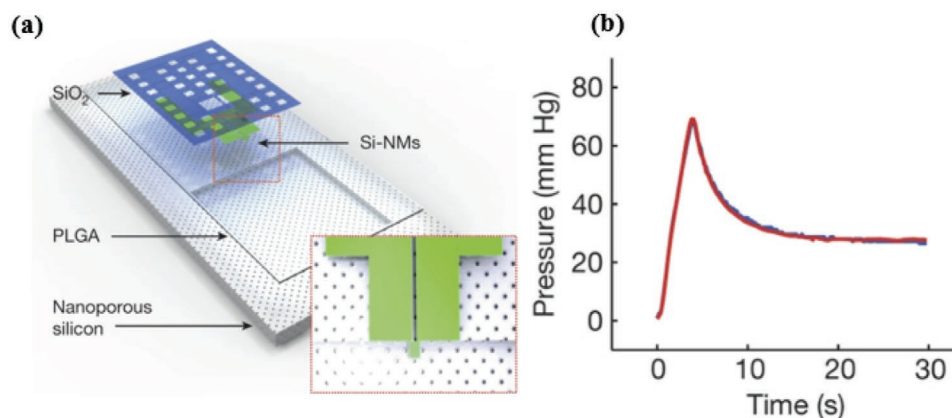


Figure 15. a) Schematic illustration of a biodegradable pressure sensor. The inset shows the location of the Si-NM strain gauge, b) Responses of a commercial pressure sensor (blue) and a calibrated biodegradable device (red) to time-varying pressure over a range relevant to intracranial monitoring. Reproduced with permission.^[66] Copyright 2021, Springer Nature.

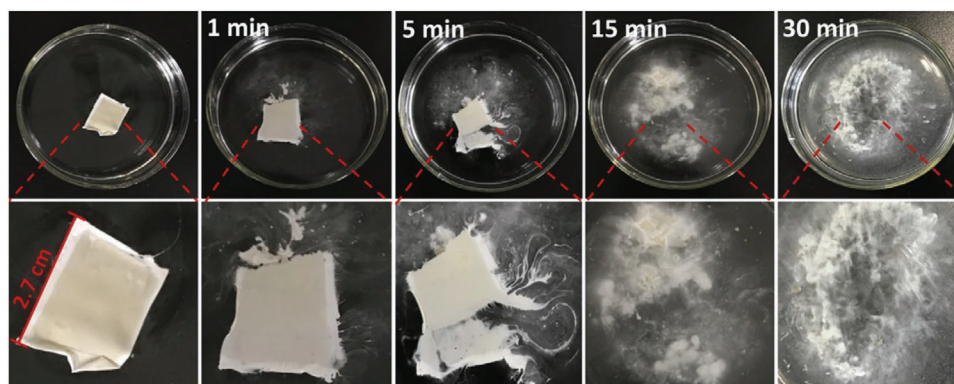


Figure 16. Optical microscope images of the transient ACCEL device. The images recording the dissolving of the sandwich structure Ag NWs/phosphor-PVP/Ag NWs ACCEL device in DI water at room temperature (Upper). Magnified optical images of the reaction of devices with water (Lower). Reproduced with permission.^[3] Copyright 2021, Springer Nature.

is demonstrated by the current–voltage relationship (I – V curve) in Figure 17c. To confirm the reliability of the resistive switching behavior, a cyclic test was done (Figure 17d), and the results prove stable endurance property over 60 cycles. Lin et al. have developed a transient switching memory device based on CsPbBr₃ thin films, which are capable of dissolving in DI water within 60 s. The fast dissolution attribute makes the device of great interest to secure memory applications.^[60,68] Pandey et al. have developed transient secured microchips that utilize the release of thermal energy or corrosive materials as their triggering mechanism. Both mechanisms demonstrated successful

destruction of the device upon triggering within a time range of less than a second to 13 s.^[5]

6. Conclusion

This review is focused on the recent developments of transient electronics technology. Materials, transiency mechanisms, manufacturing techniques, and applications of transient electronics are explored and reported in detail.

This field of technology has vast opportunities in the rapid development of advanced electronics, yet further research is

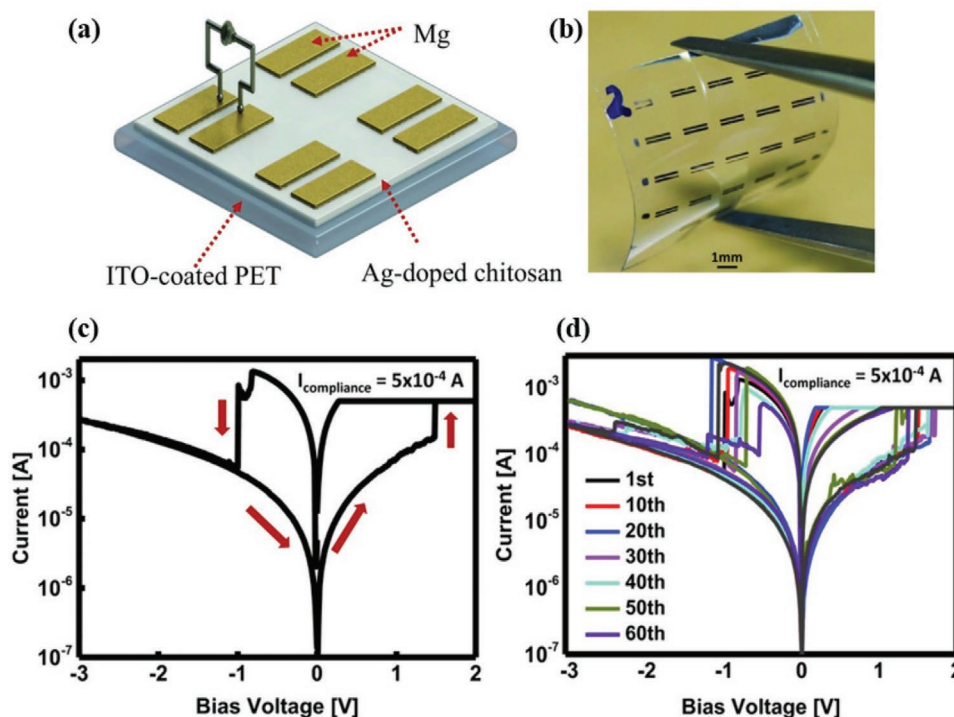


Figure 17. a) Schematic illustration of Mg/Ag-doped chitosan/Mg device structures and b) photograph of the flexible and biocompatible memory devices. c) I – V characteristics of the Mg/Ag-doped chitosan/Mg resistive switching memory device. d) Switching endurance of the chitosan-based memory device measured up to 60 cycles. Reproduced with permission.^[28] Copyright, Wiley.

essential prior to employing transient electronics technology in commercial products. One challenge that must be studied and overcome is that the transiency property of these devices should not compromise their functionality. Another challenge is the time and cost of large-scale development of transient electronics with the hitherto established materials and manufacturing techniques.

Of significant importance to the progress of this field are the design of materials and discovery of materials. Existing materials and material systems can be engineered into systems with extraordinary attributes. Also, new materials with specific properties are needed to be designed and synthesized to enable high-level tunability of the transiency mechanism while providing full functionality.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

materials degradation, polymers, sustainable systems, transient electronics, transient materials

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- [1] R. Feiner, S. Fleischer, A. Shapira, O. Kalish, T. Dvir, *J. Controlled Release* **2018**, 281, 189.
- [2] D. Son, J. Lee, D. J. Lee, R. Ghaffari, S. Yun, S. J. Kim, J. E. Lee, H. R. Cho, S. Yoon, S. Yang, *ACS Nano* **2015**, 9, 5937.
- [3] Y. Chen, H. Lu, F. Xiu, T. Sun, Y. Ding, J. Liu, W. Huang, *Sci. Rep.* **2018**, 8, 6408.
- [4] S. G. A., S. Jenny, D. V. Filippo, C. Giuseppe, R. Francesco, J. Petar, K. Stefan, D. Alwin, B. Lars, P. Luisa, K. Norbert, H. Raoul, M. Michele, T. Gerhard, *Adv. Funct. Mater.* **2017**, 27, 1702390.
- [5] S. S. Pandey, N. Banerjee, Y. Xie, C. H. Mastrangelo, *Adv. Mater. Technol.* **2018**, 3, 1800044.
- [6] J. Sun, H. Wang, F. Song, Z. Wang, B. Dang, M. Yang, H. Gao, X. Ma, Y. Hao, *Small* **2018**, 14, 1800945.
- [7] D.-H. Kim, J. Viventi, J. J. Amsden, J. Xiao, L. Vigeland, Y.-S. Kim, J. A. Blanco, B. Panilaitis, E. S. Frechette, D. Contreras, *Nat. Mater.* **2010**, 9, 511.
- [8] a) C. Legnani, C. Vilani, V. Calil, H. Barud, W. Quirino, C. Achete, S. Ribeiro, M. Cremona, *Thin Solid Films* **2008**, 517, 1016; b) M. Irimia-Vladu, P. A. Troshin, M. Reisinger, L. Shmygleva, Y. Kanbur, G. Schwabegger, M. Bodea, R. Schwödiauer, A. Mumyatov, J. W. Fergus, *Adv. Funct. Mater.* **2010**, 20, 4069.
- [9] C. J. Bettinger, Z. Bao, *Adv. Mater.* **2010**, 22, 651.
- [10] S. W. Hwang, H. Tao, D. H. Kim, H. Cheng, J. K. Song, E. Rill, M. A. Brenckle, B. Panilaitis, S. M. Won, Y. S. Kim, Y. M. Song, K. J. Yu, A. Ameen, R. Li, Y. Su, M. Yang, D. L. Kaplan, M. R. Zakin, M. J. Slepian, Y. Huang, F. G. Omenetto, J. A. Rogers, *Science* **2012**, 337, 1640.
- [11] S. W. Hwang, D. H. Kim, H. Tao, T. i. Kim, S. Kim, K. J. Yu, B. Panilaitis, J. W. Jeong, J. K. Song, F. G. Omenetto, *Adv. Funct. Mater.* **2013**, 23, 4087.
- [12] a) M. Luo, A. W. Martinez, C. Song, F. Herrault, M. G. Allen, *J. Microelectromech. Syst.* **2014**, 23, 4; b) S. W. Hwang, S. K. Kang, X. Huang, M. A. Brenckle, F. G. Omenetto, J. Rogers, *Adv. Mater.* **2015**, 27, 47.
- [13] S.-W. Hwang, J.-K. Song, X. Huang, H. Cheng, S.-K. Kang, B. H. Kim, J.-H. Kim, S. Yu, Y. Huang, J. A. Rogers, *Adv. Mater.* **2014**, 26, 3905.
- [14] L. Yin, X. Huang, H. Xu, Y. Zhang, J. Lam, J. Cheng, J. A. Rogers, *Adv. Mater.* **2014**, 26, 5.
- [15] a) Y. Chen, R. Jamshidi, K. White, S. Çinar, E. Gallegos, N. Hashemi, R. Montazami, *J. Polym. Sci., Part B: Polym. Phys.* **2016**, 54, 2021; b) S. Çinar, R. Jamshidi, Y. Chen, N. Hashemi, R. Montazami, *J. Polym. Sci., Part B: Polym. Phys.* **2016**, 54, 517.
- [16] D.-H. Kim, Y.-S. Kim, J. Amsden, B. Panilaitis, D. L. Kaplan, F. G. Omenetto, M. R. Zakin, J. A. Rogers, *Appl. Phys. Lett.* **2009**, 95, 133701.
- [17] S.-W. Hwang, H. Tao, D.-H. Kim, H. Cheng, J.-K. Song, E. Rill, M. A. Brenckle, B. Panilaitis, S. M. Won, Y.-S. Kim, *Science* **2012**, 337, 1640.
- [18] H. Tao, M. A. Brenckle, M. Yang, J. Zhang, M. Liu, S. M. Siebert, R. D. Averitt, M. S. Manno, M. C. McAlpine, J. A. Rogers, D. L. Kaplan, F. G. Omenetto, *Adv. Mater.* **2012**, 24, 1067.
- [19] C. Dagdeviren, S. W. Hwang, Y. Su, S. Kim, H. Cheng, O. Gur, R. Haney, F. G. Omenetto, Y. Huang, J. A. Rogers, *Small* **2013**, 9, 3398.
- [20] a) X. Wang, J. A. Kluge, G. G. Leisk, D. L. Kaplan, *Biomaterials* **2008**, 29, 1054; b) X. Hu, K. Shmelev, L. Sun, E.-S. Gil, S.-H. Park, P. Cebe, D. L. Kaplan, *Biomacromolecules* **2011**, 12, 1686.
- [21] G. Mattana, D. Briand, A. Marette, A. V. Quintero, N. F. De Rooij, *Org. Electron.* **2015**, 17, 77.
- [22] a) H. Li, Y. J. Tan, S. Liu, L. Li, *ACS Appl. Mater. Interfaces* **2018**, 10, 11164; b) J. Yoon, J. Han, B. Choi, Y. Lee, Y. Kim, J. Park, M. Lim, M.-H. Kang, D. H. Kim, D. M. Kim, *ACS Nano* **2018**, 12, 6006; c) S. H. Jin, J. Shin, I.-T. Cho, S. Y. Han, D. J. Lee, C. H. Lee, J.-H. Lee, J. A. Rogers, *Appl. Phys. Lett.* **2014**, 105, 013506.
- [23] H. Acar, S. Çinar, M. Thunga, M. R. Kessler, N. Hashemi, R. Montazami, *Adv. Funct. Mater.* **2014**, 24, 4135.
- [24] R. Li, H. Cheng, Y. Su, S.-W. Hwang, L. Yin, H. Tao, M. A. Brenckle, D.-H. Kim, F. G. Omenetto, J. A. Rogers, Y. Huang, *Adv. Funct. Mater.* **2013**, 23, 3106.
- [25] A. H. Najafabadi, A. Tamayol, N. Annabi, M. Ochoa, P. Mostafalu, M. Akbari, M. Nikkhah, R. Rahimi, M. R. Dokmeci, S. Sonkusale, B. Ziaie, A. Khademhosseini, *Adv. Mater.* **2014**, 26, 5823.
- [26] S.-W. Hwang, C. H. Lee, H. Cheng, J.-W. Jeong, S.-K. Kang, J.-H. Kim, J. Shin, J. Yang, Z. Liu, G. A. Ameer, *Nano Lett.* **2015**, 15, 2801.
- [27] S. K. Kang, S. W. Hwang, S. Yu, J. H. Seo, E. A. Corbin, J. Shin, D. S. Wie, R. Bashir, Z. Ma, J. A. Rogers, *Adv. Funct. Mater.* **2015**, 25, 1789.
- [28] N. R. Hosseini, J. S. Lee, *Adv. Funct. Mater.* **2015**, 25, 5586.
- [29] S.-W. Hwang, G. Park, H. Cheng, J.-K. Song, S.-K. Kang, L. Yin, J.-H. Kim, F. G. Omenetto, Y. Huang, K.-M. Lee, J. A. Rogers, *Adv. Mater.* **2014**, 26, 1992.
- [30] X. Wang, W. Xu, P. Chatterjee, C. Lv, J. Popovich, Z. Song, L. Dai, M. Y. S. Kalani, S. E. Haydel, H. Jiang, *Adv. Mater. Technol.* **2016**, 1, 1600059.
- [31] H. L. Hernandez, S. K. Kang, O. P. Lee, S. W. Hwang, J. A. Kaitz, B. Inci, C. W. Park, S. J. Chung, N. R. Sottos, J. S. Moore, J. A. Rogers, S. R. White, *Adv. Mater.* **2014**, 26, 7637.
- [32] C. W. Park, S. K. Kang, H. L. Hernandez, J. A. Kaitz, D. S. Wie, J. Shin, O. P. Lee, N. R. Sottos, J. S. Moore, J. A. Rogers, S. R. White, *Adv. Mater.* **2015**, 27, 3783.
- [33] A. M. Feinberg, H. L. Hernandez, C. L. Plantz, E. B. Mejia, N. R. Sottos, S. R. White, J. S. Moore, *ACS Macro Lett.* **2017**, 7, 47.
- [34] L. Yin, A. B. Farimani, K. Min, N. Vishal, J. Lam, Y. K. Lee, N. R. Aluru, J. A. Rogers, *Adv. Mater.* **2015**, 27, 1857.

- [35] L. Yin, H. Cheng, S. Mao, R. Haasch, Y. Liu, X. Xie, S. W. Hwang, H. Jain, S. K. Kang, Y. Su, *Adv. Funct. Mater.* **2014**, 24, 645.
- [36] S. W. Hwang, G. Park, H. Cheng, J. K. Song, S. K. Kang, L. Yin, J. H. Kim, F. G. Omenetto, Y. Huang, K. M. Lee, *Adv. Mater.* **2014**, 26, 1992.
- [37] S.-K. Kang, G. Park, K. Kim, S.-W. Hwang, H. Cheng, J. Shin, S. Chung, M. Kim, L. Yin, J. C. Lee, *ACS Appl. Mater. Interfaces* **2015**, 7, 9297.
- [38] S. K. Kang, S. W. Hwang, H. Cheng, S. Yu, B. H. Kim, J. H. Kim, Y. Huang, J. A. Rogers, *Adv. Funct. Mater.* **2014**, 24, 4427.
- [39] S. W. Hwang, X. Huang, J. H. Seo, J. K. Song, S. Kim, S. Hage-Ali, H. J. Chung, H. Tao, F. G. Omenetto, Z. Ma, *Adv. Mater.* **2013**, 25, 3526.
- [40] Z. Zhang, M. Tsang, I.-W. Chen, *Nanoscale* **2016**, 8, 15048.
- [41] X. He, J. Zhang, W. Wang, W. Xuan, X. Wang, Q. Zhang, C. G. Smith, J. Luo, *ACS Appl. Mater. Interfaces* **2016**, 8, 10954.
- [42] L. Yin, H. Cheng, S. Mao, R. Haasch, Y. Liu, X. Xie, S.-W. Hwang, H. Jain, S.-K. Kang, Y. Su, R. Li, Y. Huang, J. A. Rogers, *Adv. Funct. Mater.* **2014**, 24, 645.
- [43] L. Mengdi, A. W. Martinez, S. Chao, F. Herrault, M. G. Allen, *J. Microelectromech. Syst.* **2014**, 23, 4.
- [44] a) R. Jamshidi, S. Çinar, Y. Chen, N. Hashemi, R. Montazami, *J. Polym. Sci., Part B: Polym. Phys.* **2015**, 53, 1603; b) R. Jamshidi, Y. Chen, K. White, N. Moehring, R. Montazami, *MRS Adv.* **2016**, 1, 2501.
- [45] G. Lee, Y. S. Choi, H.-J. Yoon, J. A. Rogers, *Matter* **2020**, 3, 1031.
- [46] B. K. Mahajan, X. W. Yu, W. Shou, H. Pan, X. Huang, *Small* **2017**, 13, 1700065.
- [47] H. Li, C. C. Zhao, X. X. Wang, J. P. Meng, Y. Zou, S. Noreen, L. M. Zhao, Z. Liu, H. Ouyang, P. C. Tan, M. Yu, Y. B. Fan, Z. L. Wang, Z. Li, *Adv. Sci.* **2019**, 6, 1801625.
- [48] K. Fu, Z. Liu, Y. G. Yao, Z. Y. Wang, B. Zhao, W. Luo, J. Q. Dai, S. D. Lacey, L. H. Zhou, F. Shen, M. Kim, L. Swafford, L. Sengupta, L. B. Hu, *Nano Lett.* **2015**, 15, 4664.
- [49] S. K. Kang, G. Park, K. Kim, S. W. Hwang, H. Y. Cheng, J. H. Shin, S. J. Chung, M. Kim, L. Yin, J. C. Lee, K. M. Lee, J. A. Rogers, *ACS Appl. Mater. Interfaces* **2015**, 7, 9297.
- [50] a) Y. Chen, R. Jamshidi, W. Hong, R. Montazami, *Adv. Mater. Interfaces* **2017**, 4, 1601076; b) Y. Chen, R. Jamshidi, W. Hong, N. N. Hashemi, R. Montazami, *Adv. Eng. Mater.* **2017**, 19, 201600592.
- [51] a) M. Tsang, A. Armutlulu, A. W. Martinez, S. A. B. Allen, M. G. Allen, *Microsyst. Nanoeng.* **2015**, 1, 1; b) X. Y. Huang, D. Wang, Z. Y. Yuan, W. S. Xie, Y. X. Wu, R. F. Li, Y. Zhao, D. Luo, L. Cen, B. B. Chen, H. Wu, H. X. Xu, X. Sheng, M. L. Zhang, L. Y. Zhao, L. Yin, *Small* **2018**, 14, 1800994; c) Y. S. Choi, J. Koo, Y. J. Lee, G. Lee, R. Avila, H. Ying, J. Reeder, L. Hambitzer, K. Im, J. Kim, *Adv. Funct. Mater.* **2020**, 30, 2000941.
- [52] W. D. Chen, S. K. Kang, W. J. Stark, J. A. Rogers, R. N. Grass, *Sens. Actuators, B* **2019**, 282, 52.
- [53] Y. Gao, K. Sim, X. Yan, J. Jiang, J. Xie, C. Yu, *Sci. Rep.* **2017**, 7, 947.
- [54] D. Liu, S. Zhang, H. Cheng, R. Peng, Z. Luo, *Sci. Rep.* **2019**, 9, 1.
- [55] H. L. Hernandez, O. P. Lee, C. M. P. Casey, J. A. Kaitz, C. W. Park, C. L. Plantz, J. S. Moore, S. R. White, *Macromol. Rapid Commun.* **2018**, 39, 1800046.
- [56] a) S.-W. Hwang, G. Park, C. Edwards, E. A. Corbin, S.-K. Kang, H. Cheng, J.-K. Song, J.-H. Kim, S. Yu, J. Ng, J. E. Lee, J. Kim, C. Yee, B. Bhaduri, Y. Su, F. G. Omenetto, Y. Huang, R. Bashir, L. Goddard, G. Popescu, K.-M. Lee, J. A. Rogers, *ACS Nano* **2014**, 8, 5843; b) Y. Gao, Y. Zhang, X. Wang, K. Sim, J. S. Liu, J. Chen, X. Feng, H. X. Xu, C. J. Yu, *Sci. Adv.* **2017**, 3, e1701222.
- [57] J. Reihaneh, Ç. Simge, C. Yuanfen, H. Nastaran, M. Reza, *J. Polym. Sci., Part B: Polym. Phys.* **2015**, 53, 1603.
- [58] a) M. J. Tan, C. Owh, P. L. Chee, A. K. K. Kyaw, D. Kai, X. J. Loh, *J. Mater. Chem. C* **2016**, 4, 5531; b) A. Teichler, J. Perelaer, U. S. Schubert, *J. Mater. Chem. C* **2013**, 1, 1910; c) K. Suganuma, *Introduction to Printed Electronics*, Vol. 74, Springer Science & Business Media, Berlin **2014**; d) B. J. de Gans, P. C. Duineveld, U. S. Schubert, *Adv. Mater.* **2004**, 16, 203.
- [59] Y. Chen, R. Jamshidi, R. Montazami, *Materials* **2020**, 13, 1112.
- [60] L. Lu, Z. Yang, K. Meacham, C. Cvetkovic, E. A. Corbin, A. Vázquez-Guardado, M. Xue, L. Yin, J. Boroumand, G. Pakeltis, *Adv. Energy Mater.* **2018**, 8, 1703035.
- [61] a) W. Xue, P. Li, in *Carbon Nanotubes: Synthesis, Characterization, Applications* (Ed: S. Yellampalli), IntechOpen, London, UK **2011**, pp. 171–190; b) M. Sessolo, D. Khodagholy, J. Rivnay, F. Maddalena, M. Gleyzes, E. Steidl, B. Buisson, G. G. Malliaras, *Adv. Mater.* **2013**, 25, 2135; c) M. Rothschild, T. M. Bloomstein, T. H. Fedynyshyn, R. R. Kunz, V. Liberman, M. Switkes, N. N. Efremow, S. T. Palmacci, J. H. Sedlacek, D. E. Hardy, *Lincoln Lab. J.* **2003**, 14, 221; d) K. Salaita, Y. Wang, C. A. Mirkin, *Nat. Nanotechnol.* **2007**, 2, 145.
- [62] S.-W. Hwang, H. Tao, D.-H. Kim, H. Cheng, J.-K. Song, E. Rill, M. A. Brenckle, B. Panilaitis, S. M. Won, Y.-S. Kim, Y. M. Song, K. J. Yu, A. Ameen, R. Li, Y. Su, M. Yang, D. L. Kaplan, M. R. Zakin, M. J. Slepian, Y. Huang, F. G. Omenetto, J. A. Rogers, *Science* **2012**, 337, 1640.
- [63] a) M. A. Meitz, Z.-T. Zhu, V. Kumar, K. J. Lee, X. Feng, Y. Y. Huang, I. Adesida, R. G. Nuzzo, J. A. Rogers, *Nat. Mater.* **2006**, 5, 33; b) S. W. Hwang, C. H. Lee, H. Y. Cheng, J. W. Jeong, S. K. Kang, J. H. Kim, J. Shin, J. Yang, Z. J. Liu, G. A. Ameer, Y. G. Huang, J. A. Rogers, *Nano Lett.* **2015**, 15, 2801.
- [64] X. Liang, Z. Fu, S. Y. Chou, *Nano Lett.* **2007**, 7, 3840.
- [65] S. W. Hwang, D. H. Kim, H. Tao, T. I. Kim, S. Kim, K. J. Yu, B. Panilaitis, J. W. Jeong, J. K. Song, F. G. Omenetto, J. A. Rogers, *Adv. Funct. Mater.* **2013**, 23, 4087.
- [66] S.-K. Kang, R. K. Murphy, S.-W. Hwang, S. M. Lee, D. V. Harburg, N. A. Krueger, J. Shin, P. Gamble, H. Cheng, S. Yu, *Nature* **2016**, 530, 71.
- [67] H. Tao, S.-W. Hwang, B. Marelli, B. An, J. E. Moreau, M. Yang, M. A. Brenckle, S. Kim, D. L. Kaplan, J. A. Rogers, *Proc. Natl. Acad. Sci. U.S.A.* **2014**, 111, 17385.
- [68] a) F. Song, H. Wang, J. Sun, H. Gao, S. Wu, M. Yang, X. Ma, Y. Hao, *IEEE Electron Device Lett.* **2017**, 39, 31; b) H. Wang, B. Zhu, X. Ma, Y. Hao, X. Chen, *Small* **2016**, 12, 2715.



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