CHEMISTRY OF MATERIALS

Perspective

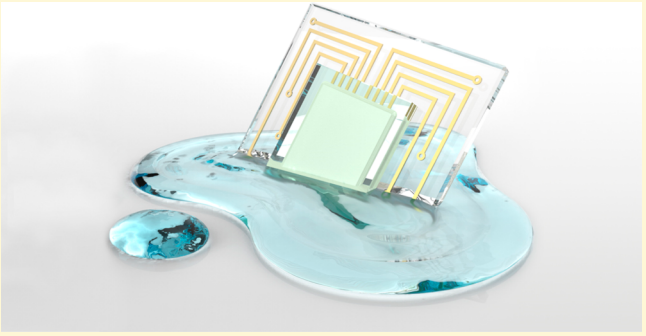
pubs.acs.org/cm

Transient Electronics: Materials and Devices†

Kun Kelvin Fu, Zhengyang Wang, Jiaqi Dai, Marcus Carter, and Liangbing Hu*

Department of Materials Science and Engineering, University of Maryland College Park, College Park, Maryland 20742, United States

ABSTRACT: Transient technology is an emerging field that requires materials, devices, and systems to be capable of disappearing with minimal or non-traceable remains over a period of stable operation. Electronics with the capability of disintegrating or vanishing after stable operation are becoming an interesting research topic and have attracted increasing attentions. In recent years, transience technology has been extended to intelligence applications, bioelectronics and environmental monitoring systems, and energy harvesters and storage. Although the transient concept has only a few years of development, this emerging transient technology is believed to find more opportunities in the fast development of advanced electronics. In this review, we will examine recent progress in the development of transient electronics. First, an overview of various transient materials, including metals, polymers, and semiconductor materials, is described. Second, recent progress in the design and development of transient electronics is reviewed. Third, transient energy storage, focusing on primary batteries and secondary batteries, is explored. We end the review with a conclusion and outlook, pointing out further designs and developments of transient technology based on transient materials towards high-performance evanescent electronics and energy storage.



1. INTRODUCTION

With the rapid development of technology, large amounts of consumer electronics have been developed and discarded. Electronic waste (E-waste) has become a huge 21st-century issue that has greatly increased the demand for landfill space and simultaneously caused environmental burdens. To address these challenges, the concept of transient technology has been developed in recent years. Transient technology enables these electronics to be zero-waste; these green electronics can degradento the surrounding environment with no or minimum impact, which can address the environmental challenge. In addition to the transient, green electronics, transient devices have a variety of applications, such as transient medical devices that can eliminate the need for secondary surgeries to extract implanted devices within the human body. Transient devices as hardware-secured electronics can disappear completely by self-destruction, and transient environmental sensors can degrade naturally into the surrounding environment after certain period of operation time. Following these concepts, the design of transient electronics is required to be biocompatible, biodegradable, and environmentally friendly. Although the transient concept has only a few years of development, this emerging transient technology is believed to find more opportunities in the fast development of advanced electronics.

Transient technology requires materials and devices to "disappear" into the surrounding environment with nontraceable remains.[1] This technology concept has been extensively adopted into materials degradation behaviors,[2−7] modeling approaches,[8−10] manufacturing schemes,[3,4,7,11] device designs, and fabrications for transient devices,[1−7,12,13] systems,[11] and power supplies.[14−18] Transient electronics have been successfully designed into biomedical applications,[3,19,20] secure memory devices, and environmental sensors.[6] In these devices, components used in transient technology can maintain the full characteristics and operation with reliable performance in regular use. After being transient, the functionalities are controllably terminated and their structures disappear untraceably. The materials for encapsulation are critically important for the stable operation of transient electronics, as stable operation is defined as the performance for a specified period of time when the device is first exposed to a stimulus.[1,7,9] The transient behaviors of electronics as well as their capsulations are strongly related to the factors including material's properties, device structures, and system integrations. In addition to these intrinsic factors, the external trigger stimulus is another factor that determines the transient behavior of electronics. According to the literature, triggers include different formats, such as solution,[21] light,[21] temperature,[13] and even mechanical force to make materials transient. Since solutions are widely applied to dissolve transient electronics, generally speaking, transient electronics can be divided into two classes: fully solution soluble electronics which use water as a trigger and partially transient triggered electronics which use other types of triggers (light, temperature, and others). In comparison, solution triggering seems to be the only category, as reported so far, that can realize fully transient electronics.

†This Perspective is part of the *Up-and-Coming* series.

Received: December 21, 2015
Revised: April 27, 2016
Published: April 28, 2016

ACS Publications © 2016 American Chemical Society

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

Other triggers, for example, light and temperature, usually will only partially disintegrate or damage electronics to inhibit functionality but cannot achieve full dissolution as we defined in the transient concept. Therefore, strictly speaking, fully solution soluble electronics will be exclusively considered to be transient in this scenario and discussed in this review.

As shown in Figure 1, in this review we will examine recent progress in the development of transient electronics. First, an overview of various transient materials, including metals, polymers, and semiconductor materials, is described. Second, recent progress in the design and development of transient electronics is reviewed. Third, transient energy storage, focusing on primary batteries and secondary batteries, is explored. We end the review with a conclusion and outlook, pointing out future designs and developments of transient technology based on transient materials toward high-performance evanescent electronics and energy storage.

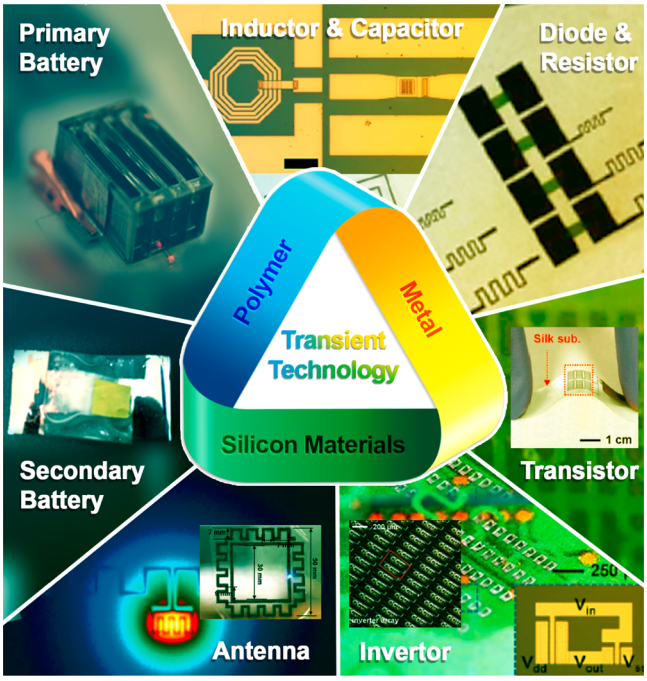


Figure 1. Overview of transient electronics: materials and devices.

2. MATERIALS

Transient materials are a type of material with transient behavior that in regular use can maintain their full characteristics and functionalities to meet reliable performance. When a solution trigger is applied, the materials will either physically or chemically disappear completely in a totally or partially controlled manner. Based on recent work, transient materials can be classified into three categories: metals, polymers, and semiconductor materials. In this section, we will review the properties, structural designs, and transient behaviors of the aforementioned materials.

2.1. Metals. In electronics, conductive materials serve as electrodes and connections. Compared to conductive polymers, metals are more attractive because of their high electrical conductivity, stable properties, and established roles in commercial devices. Recently, magnesium (Mg), zinc (Zn), iron (Fe), tungsten (W), and molybdenum (Mo) have been studied as dissolvable metals for transient electronics. Each of these metals are important to biological functions and can be potentially used in biomedical implants.[2] For example, Mg, Mg alloys, and Fe have been used in the design of bioresorbable implants, such as vascular stents, due to the good biocompatibility and favorable mechanical properties. As important electronic components, therefore, it is important to systematically study and understand the transient behavior of these promising candidates in the applications of biomedical implants, environmental monitors, and others. In this section, we will review the recent developments of dissolvable metal thin films in terms of their electrical conductivity, thickness, morphology, and surface chemistry during dissolution and explore the electrical properties of transient electronic devices based on various metals.

Figure 2 shows changes in the resistance and in the thickness as a function of time for various metal films in deionized (DI) water and simulated body fluids (Hanks' solutions, pH values between 5 and 8) at both room temperature and body temperature (37 °C). Electrical dissolution rates (EDR), which are defined by converting changes in electrical resistance to an effective thickness, are used to describe the transient behavior as a function of time. AZ31B is Mg alloy containing 3 wt % Al and 1 wt % Zn. Compared in Figure 2, Mg, Mg alloy, and Zn exhibited higher dissolution in Hanks solutions than in DI water. The increased rates of dissolution are due to the acidic conditions or the presence chlorides in basic and neutral condition promoting rapid attack in the corrosion process of these metals. Mo showed an opposite result; the EDR in DI water is higher in Hanks solutions than at room temperature. W exhibited an EDR in acidic salt solution (pH 5) much lower than in more basic solutions with higher pH values (pH 7.4–8). In addition, chemical vapor deposition formed W has an order of magnitude lower EDR than the sputtered W. Fe exhibited the highest EDR for acidic solution (pH 5) and for basic solution (pH 7.4 at 37 °C).

Mg was reported to be used as the electrodes and interconnects in silicon transient electronics by Hwang et al. in 2012.[1] This selection is mainly due to the combination of the ease in processing, fast rates of hydrolysis, and favorable biocompatibility.[22−25] A representative work reporting an evaluation of microstructure and surface chemistry of Mg during its dissolution in DI water was conducted by Yin et al.[2] from the Rogers's group. The Mg thin film was fabricated as shown in Figure 3a. The Mg exhibited a uniform dissolution in at macroscopic scale in DI water as shown in Figure 3a–d. On the nanoscale, micropores developed, the surface became roughened, and needle-like structure formed during the dissolution process (Figure 3e–h). The needle-like dissolution products were Mg oxide derivatives, including MgO and $Mg(OH)_2$, which were confirmed by the X-ray photoelectron spectroscopy (XPS). During dissolution, the outer surface was mainly composed of $Mg(OH)_2$. $Mg(OH)_2$ is the major product of Mg corrosion in the Hanks's solutions. The transmission electron microscopy (TEM) images illustrated the Mg and the needle-like oxide products, indicating the presence of crystalline MgO and amorphous $Mg(OH)_2$. This $Mg(OH)_2$ layer could increase in thickness as the dissolution proceeds. As time proceeds, only residual $Mg(OH)_2$ and MgO remained. Due to their high solubility in water, these salt products will dissolve eventually. Other metals including W, Mo, and Zn followed similar transient behavior in DI and Hanks' solutions.

In general, Mg and Zn undergo a fast transient behavior in DI water and biological solutions, and W and Mo follow slow but predictable degradation rates. These behaviors provide multiple options to meet the various requirements of degradation times

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

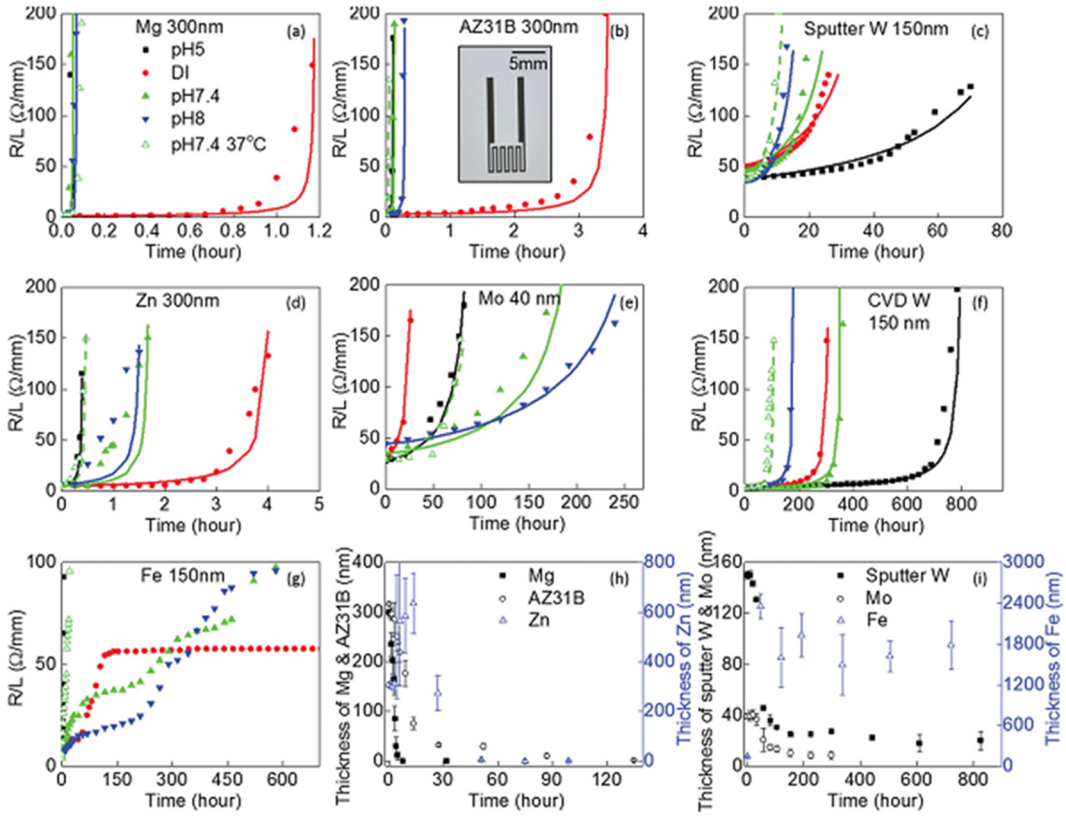


Figure 2. Changes in resistance of metal films and changes in thickness as a function of time during dissolution in Hanks' solutions and in DI water at room temperature and 37 °C. Reprinted with permission from ref 2. Copyright 2014 Wiley.

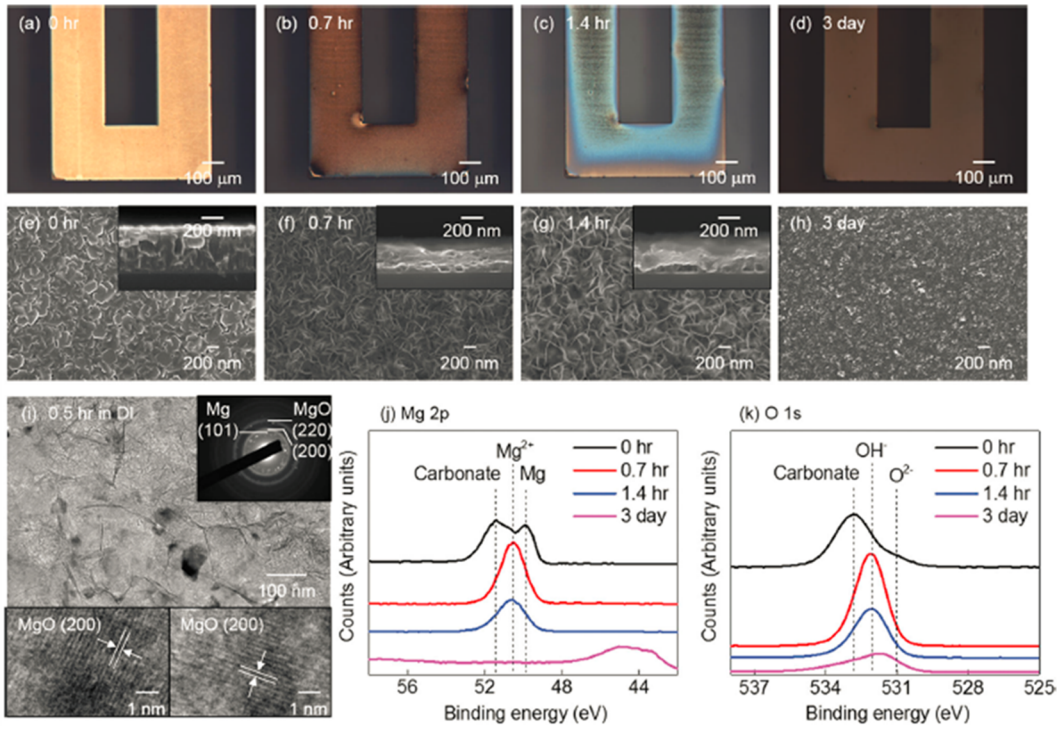


Figure 3. Evolution of the microstructure and surface chemistry associated with dissolution of Mg in DI water. (a–d) optical images; (e–h) SEM images with cross-sectional views in the insets; (i) TEM bright field image with diffraction patterns and lattice fringes; (j, k) XPS data to study the transient behavior of Mg based material. Reprinted with permission from ref 2. Copyright 2014 Wiley.

for different applications. For a slow transient requirement, such as medical devices which require metals to have direct contact with biological tissues for signal sensing, W and Mo can be selected due to their slow and controlled degradation rates. For a

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527–3539

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

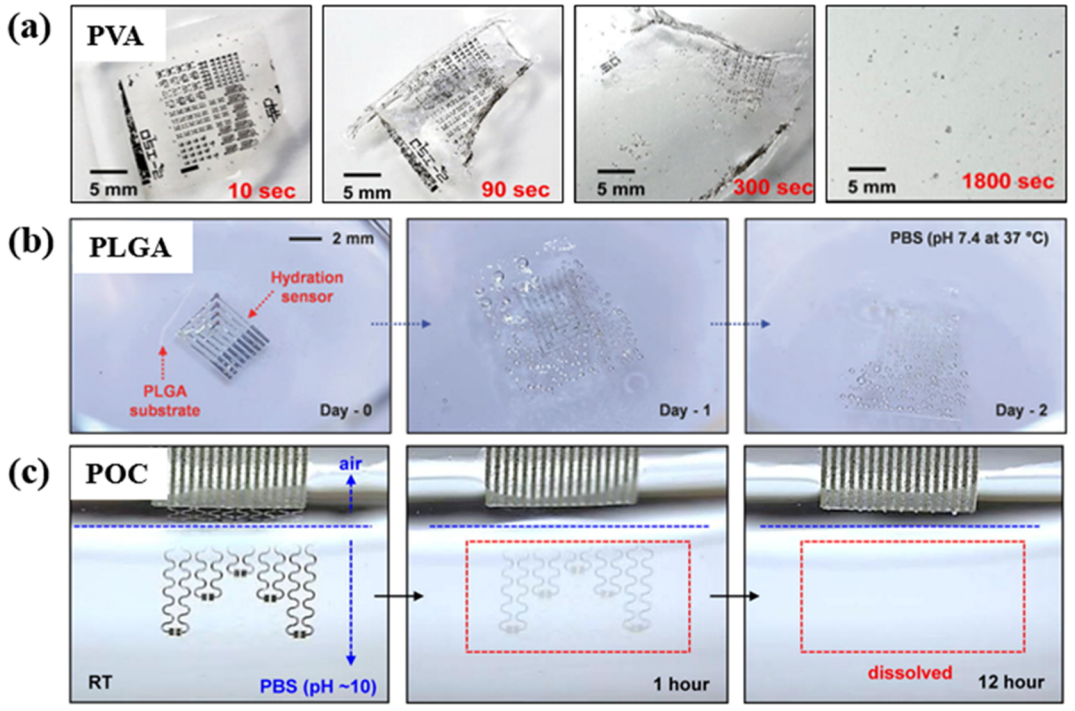


Figure 4. Dissolution evolutions of water-soluble polymer substrate (a) PVA,[26] (b) PLGA,[5] and (c) POC.[6] Reprinted with permission from refs 26, 5, and 6. Copyright 2014 American Institute of Physics, 2014 Wiley, and 2015 American Chemical Society.

rapid transient requirement, such as secure electronics that need to disappear within a limited time range, Mg and Zn can be considered.

2.2. Polymer. *2.2.1. Water-Soluble Polymers.* Water-soluble polymers cover a wide range of materials with various applications and include paint, textiles, paper, and coatings. These polymers are substituted or incorporated with some hydrophilic groups into their backbone that can dissolve, disperse, or swell in water. Typical water-soluble polymers include poly(vinyl alcohol) (PVA), polyvinylpyrrolidone (PVP), polylacticcoglycolic acid (PLGA), polylactic acid (PLA), and polycaprolactone (PCL).[5] For instance, PVA is widely applied into the transient electronics as supporting substrates and encapsulation materials. PVA is synthesized by the polymerization of vinyl acetate to polyvinyl acetate (PVAc) and then hydrolyzed to generate the alcohol. Because PVA has a hydroxyl group in its structure, it is soluble in highly polar and hydrophilic solvents like water and *N*-methyl pyrrolidone (NMP). PVA has certain advantages, including being nontoxic, noncarcinogenic, and soluble in many solvents, which make it an ideal candidate for transient electronics with biomedical applications. Recently, Jin et al. used PVA as a substrate for transient single-walled carbon nanotube field effect transistors (FET).[26] In Figure 4a, the PVA film with a 30 μm thickness was immersed in DI water for dissolution testing. It quickly swelled and began to dissolve instantly upon the introduction of the trigger solution. The substrate was completely dissolved in 30 min. As previously mentioned, a controllable degradation is critical to the systematical design of transient materials with multiple purposes. Generally, the solubility of PVA in water relies on the degree of polymerization (DP) and solution temperature. A tunable degradation can be achieved by controlling the composite structure and the ratio of each of the material components. Acar et al. found the dissolution rate of PVA polymer in water can be easily adjusted by simply adding gelatin or sucrose to a PVA polymer matrix.[27] The addition of sucrose to the PVA film increased the dissolution rate, while the incorporation of gelatin decreased the dissolution rate. Therefore, the dissolution evolution of a PVA substrate can be programmed by controlling the composite structure.

PVP is another water-soluble polymer widely applied in numerous applications. Fu et al. used PVP membrane as a transient separator in a transient rechargeable lithium ion battery.[16] In this case, the PVP fiber was prepared by an electrospinning method. The fiber had an average diameter of 600 nm with porous nonwoven structure for lithium ion diffusion. The PVP membrane disassociated in DI water within 10 min indicating an excellent transience property.

PLGA is a water-soluble polymer applied in transient electronics. PLGA is a copolymer of PLA and PGA with ability to tunably degrade by adjusting molecular weight and the ratio of components. Specifically, the hydrophobicity of PLGA can be increased by the enhancement of PLA components, whereas the addition of PGA components leads to hydrophobicity with a longer transience process. The dissolution test of PLGA was conducted by Hwang et al. as shown in Figure 4b.[5] In their work, a transient hydration sensor was placed on a PLGA substrate, and the transient trigger was a phosphate buffer solution (PBS, 1 M, pH 7.4) at a physiological temperature (37 °C). After 2 days, the sensor materials had mostly dissolved and the remaining PLGA substrate dissolved over a month.

For transient electronics, stretchable substrates are important to offer opportunities to adapt to human bodies. In this case, a biodegradable elastomer is an ideal material to meet this requirement. Elastomers are a kind of polymer with viscoelasticity and weak intermolecular forces. Suk-Won Hwang[6] used biodegradable elastomer poly(1,8-octanediol-*co*-citrate) (POC) to make a substrate, which can be stretched up to ~30%, for flexible transient electronic devices. In addition, POC also served as encapsulation materials protecting the device from

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

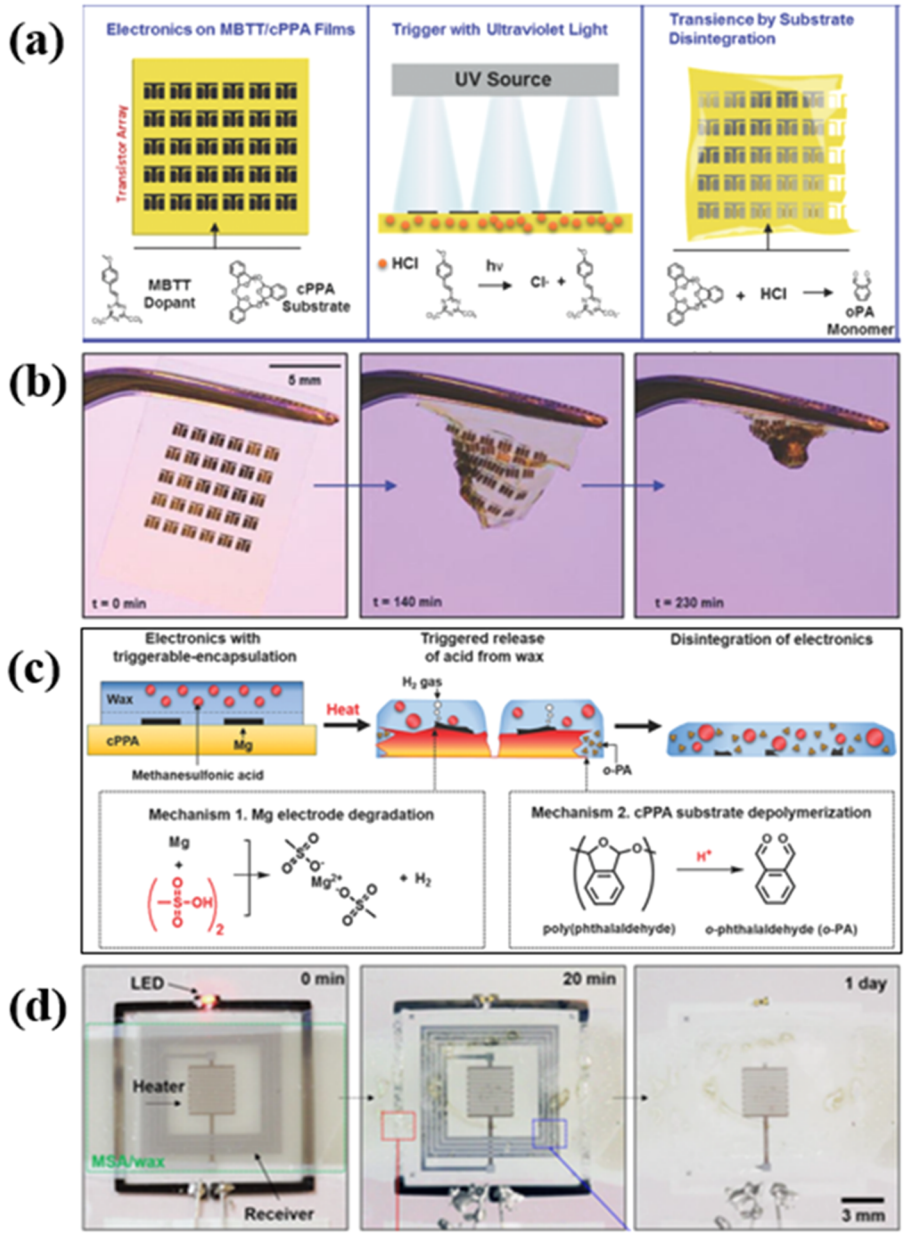


Figure 5. Acid soluble polymer dissolution and mechanism. (a) Schematic of acid triggered polymer (MBTT/cPPA) dissolution mechanism.[21] (b) Experimental dissolution of MBTT/cPPA. (c) Schematic of heat triggered polymer (wax/cPPA) dissolution mechanism. (d) Experimental transience of the waxy coating polymer.[13] Reprinted with permission from refs 21 and 13. Copyright 2014 and 2015 Wiley.

the ambient environment. The dissolution evolution of POC was triggered by phosphate buffered saline (PBS, pH 10) at room temperature (Figure 4c). The electronic materials dissolved quickly and disappeared within 12 h, while the rest POC substrate remain visible for several weeks. Like other polymers, the dissolution rate of POC is strongly influenced by factors like temperature, pH value, solution concentration, and the morphologies of the materials.

2.2.2. Acid Soluble Polymer. Most transient devices are designed for biocompatible applications and, thus, are capable of degrading in buffered solutions. Therefore, the design of water-soluble materials (both metal and polymer) has been sufficiently studied for buffered and neutral solutions.

Compared to neutral triggers, acid based triggers have faster rates of transience which have wide applications to devices that do not require biocompatibility but need to disappear entirely or require a complete destruction of the electronic components such as metals and metal oxides. Hernandez et al.[21] applied acids into the transient electronics field by introducing poly-(phthalaldehyde) (PPA) as a substrate material. PPA is a typical metastable polymer, which can be self-depolymerized back into monomers once triggered by a specific stimulus like acid.[28] Further developments used UV-light triggered polymer 2-(4-methoxystyryl)-4,6-bis(trichloromethyl)-1,3,5-triazine (MBTT) as a photoacid generator that was linked with the backbone of cyclic PPA (cPPA). In Figure 5a, a MBTT/cPPA film served as substrate for a transience system. When exposed to 379 nm UV-light, the MBTT additive generates a highly reactive $Cl^{\bullet}$ radical that captures a hydrogen from its surroundings to form hydrochloric acid (HCl), and this as-generated HCl reacts with cPPA to trigger the depolymerization by cleaving of the acetal backbone of cPPA. Figure 5b shows an array of transistors with a

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

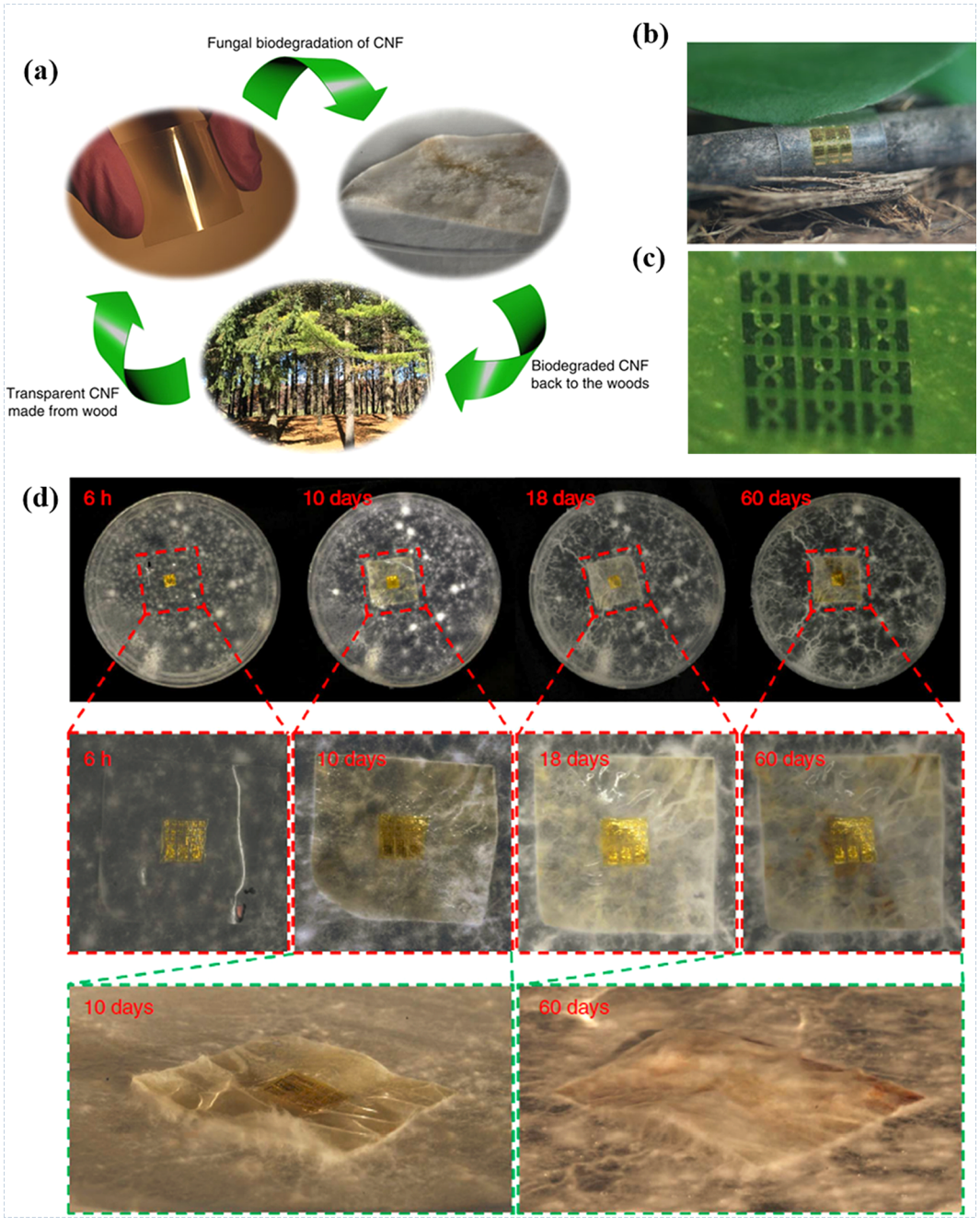


Figure 6. Biomass-based transient electronics: (a) Illustration of a prospective life cycle of the biobased and biodegradable CNF paper. (b) Photograph of an array of HBTs on a CNF substrate. (c) Magnified image of the array. (d) A series of photographs taken at 6 h, 10 days, 18 days, and 60 days after starting the degradation process. (e) A series of magnified photographs of the CNF-based electronics during the degradation process. (f) Tilted-view photograph of the CNF-based electronics after 10 days and 60 days of degradation. The fungus fully covers the film after 60 days. Reprinted with permission from ref 29. Copyright 2015 Nature Publishing Group.

2.5% MBTT/cPPA freestanding film. The MBTT/cPPA film was initially robust under ambient conditions. After being exposed to a UV lamp, the cPPA film transformed from a free-standing film to an oily agglomerated remnant as the depolymerization occurred. The degradation process lasted 230 min. This work offered a novel avenue for transient electronics with a wider selection of materials, functionalities, and capacities.

Upon careful consideration of the difficulties of photoacid generator additive synthesis, Park et al.[13] employed heat as a stimulus to trigger the dissociation of a polymer substrate. In Figure 5c, cPPA served as the substrate of an electronic device which encapsulated Mg and acid which were separated by a layer of protective wax. Methanesulfonic acid (MSA) was selected to dissolve both the substrate and Mg to achieve a totally self-destructive transient device. When exposed to a heat source, the melting of the wax releases the encapsulated acid which leads to a rapid self-depolymerization of the cPPA substrate. Figure 5d shows a self-destructive device with an inductive heater (Mg/SiO_2/Mg) and LED interconnected by Mg on glass with MSA/wax encapsulation. The resistive heater was wirelessly powered through inductive coupling and immediately heated the device to

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

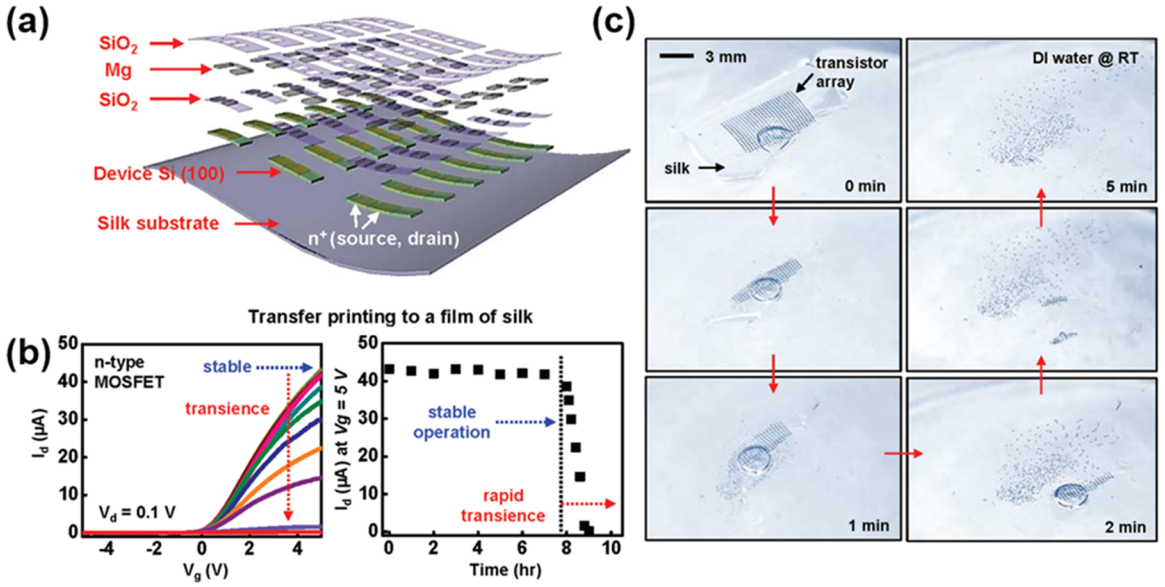


Figure 7. (a) Schematic of an array of MOSFETs after transfer printing to a silk substrate. (b) Electrical properties of MOSFETs encapsulated with MgO measured at various times during immersion in water at room temperature. (c) Dissolution of MOSFETs at various times during immersion in water at room temperature. Reprinted with permission from ref 3. Copyright 2013 Wiley.

the melting temperature of the wax. When wax melted, the acid stored inside was released, which caused the substrate and electronics to dissolve within 20 min. After 1 day, Mg-based trace was fully disintegrated, but part of the heating-resistor, protected by SiO_2 (≈900 nm thick), remained intact.

2.2.3. Green Materials. Apart from the previously mentioned synthetic polymers, green polymers such as cellulose and silk have great potential as nontoxic and biodegradable materials for transient electronics. The Rogers group used silk polymer as a biodegradable substrate to integrate with Si semiconductors to fabricate electronics.[1,3] Ma's group reported the use of cellulose nanofibril paper as a flexible substrate for green flexile electronics.[29] The Hu group developed flexible organic field-effect transistors (OFETs) with highly transparent nanocellulose paper.[30−32] These materials, especially cellulose-based materials, show excellent degradation capabilities, good biocompatibility, high performance, and low cost, demonstrating great potential for large-scale fabrication of electronics in an eco-friendly way.

Figure 6a shows the life cycle of a cellulose nanofibril film, which comes from the fibers extracted from wood, then degrades via fungal biodegradation, and finally goes back into nature. This cycle would not create an environmental burden and achieves completely "green" transience. In Figure 6b, an array of heterojunction bipolar transistors (HBT) was fabricated on a cellulose nanofibril paper. The transistor device was wrapped around a stick to demonstrate the high flexibility of the device. Figure 6c displays a magnified photograph of the array. As a proof-of-concept for biodegradable electronics, a test of fungal degradation was administered to the cellulose nanofibril paper based electronic device. Figure 6d shows the images of the degradation process of the device by using the brown rot fungus *Postia placenta*. Photos were taken after 6 h, 10 days, 18 days, and 60 days. The fungus started to cover the electronic device partially after 10 days and fully covered the sample around 60 days. Once the cellulose based substrate was degraded, the remaining electronic portion could be collected for further decomposition or recycling.

2.3. Semiconductor Materials. Electronic properties can be altered in a controllable way by the doping method. Generally, semiconducting materials are crucial to the development of electronics. Among the various semiconductor materials, silicon is one of the most widely used semiconductor materials for the electronics industry. Since silicon can dissolve in water within a certain time by hydrolysis, this is important to the design of transient electronics. For example, monocrystalline silicon (Si) nanomembranes (NMs) have served as semiconductors in circuits, and silicon oxide has been applied in transistor devices like inverters and gates.[33] The morphology of silicon is tunable, which is critical to the material's performance as well as the dissolution evolution. The dissolution mechanism of single-crystalline silicon nanomembranes (Si NM) has been studied. The mechanism demonstrated a large-area and showed uniform hydrolysis on the Si NMs, and the dissolution rate can be controlled by a wide range of aqueous solutions with different pH values. Moreover, the dissolution rate varies among semiconductors with different dopant types and dopant concentrations. Kang et al.[10] reported the dissolution chemistry of semiconductor materials including polycrystalline silicon (poly-Si), amorphous silicon (a-Si), silicon−germanium (Si−Ge), and germanium (Ge) in aqueous solutions of various pHs and temperatures. Generally, the transient rates of these semiconductor materials at physiological temperature (37 °C) are higher than those at room temperature. At specific temperatures, a more alkaline solution is a faster trigger than conventional DI water with a pH value around 7.

3. TRANSIENT DEVICES AND SYSTEMS

3.1. Transient Transistor Devices and Applications. Transient electronics represents a new type of technology that endows materials, devices, and systems with the capability of dissolving into the surrounding environment with minimal or nontraceable remains after a period of stable operation. The transient concept requires semiconductors devices and integrated systems to be capable of physically disappearing or disintegrating in certain ways. These Si semiconductors can be

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

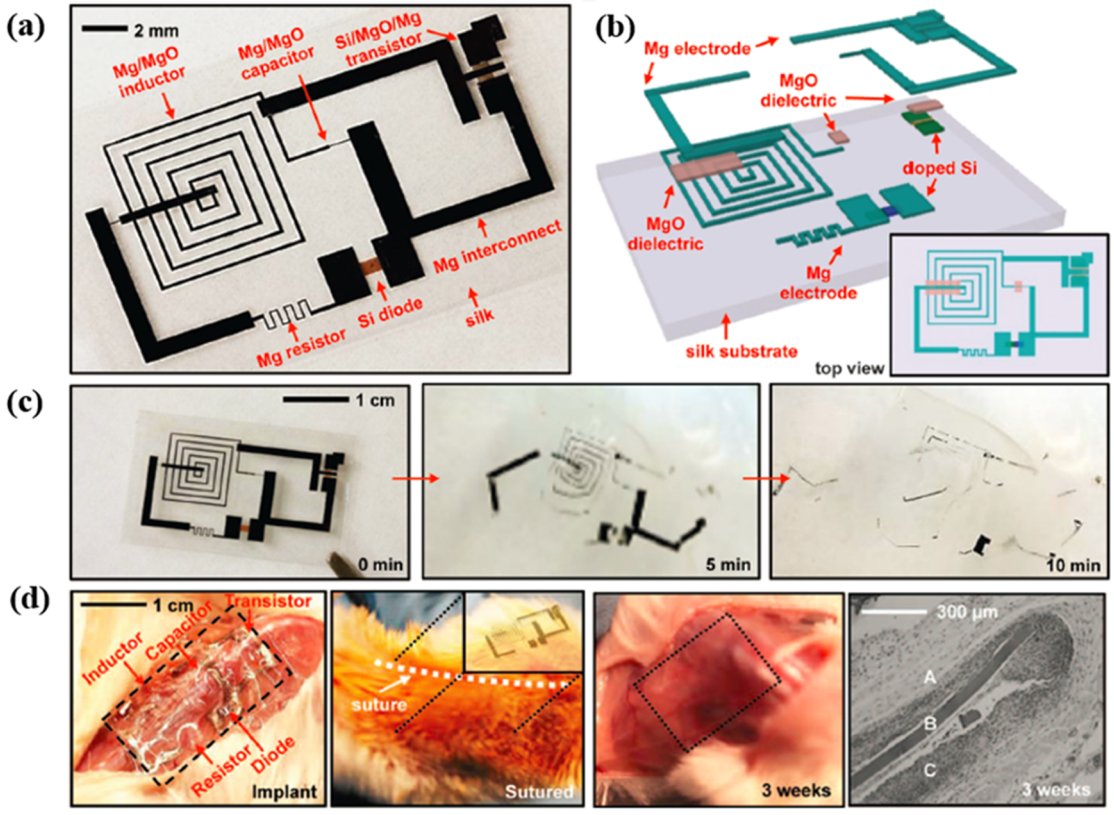


Figure 8. Transistor based devices and applications: (a) Image of a device that includes transistors, diodes, inductors, capacitors, and resistors, with interconnects and interlayer dielectrics, all on a thin silk substrate. (b) Expanded view schematic illustration, with a top view in the lower right inset. (c) Images showing the time sequence of dissolution in DI water. (d) An example of the *in vivo* evaluations of a transient device located in the subdermal dorsal region of a mouse. Reprinted with permission from ref 1. Copyright 2012 American Association for the Advancement of Science.

hydrolyzed in groundwater or biofluids with a controlled transient rate depending on temperature, pH, ionic concentration, and doping level of silicon. By using the hydrolyzable Si semiconductors, transient electronics has been demonstrated by utilizing the previously discussed transient materials, including dissolvable metals (e.g., Zn, Fe, W, Mg, Mo) as interconnects and electrodes, MgO, SiO_2, or SiN_x as dielectrics and encapsulating layers, and biodegradable polymers (e.g., silk, poly(latic-*co*-glycolic acid) (PLGA), polycaprolactone (PCL), polylactic acid (PLA)) as substrates and packaging materials. Through designing and developing transient materials and integrating them as different components together, electronic devices and systems can be made into almost any kind of transient applications, which can be categorized into four main interests: biomedical implants, environmental sensors, portable electronics, and secure memory devices. This section explores recent development in transient electronic devices and integrated systems as well as their potential applications.

The Rogers group have reported a representative strategy for materials selection and fabrication processes for transient electronics. Their devices involved water-soluble materials including Si, SiO_2, MgO, Mg, and silk.[1] The overall strategy is to move to the fabrication of circuits and circuit components on a silicon wafer, followed by controlled release from the wafer and subsequent integration onto a transient substrate by transfer printing techniques. Figure 7a represents schematic of an array of transient monocrystalline silicon metal-oxide field-effect transistors (MOSFETs) after it had been released from the substrate and was integrated onto a silk substrate using the transfer printing technique.[3] Figure 7b shows the change in electrical properties of the MOSFETs devices measured at various times during dissolution in water at room temperature. The results indicate that the device's properties are stable for the first 8 h. After being triggered by water as shown in Figure 7c, the silk substrate began to dissolve first, leading to the disintegration of the array into individual components. Each component gradually dissolves in a manner defined by the dissolution rates, which, again, are dependent on the temperature, pH, layer thickness, and morphology. The overall fabrication process also can be used for logic gates and small-scale integrated circuits.

When combined with transient circuit components, this transient technology can provide more diverse functionalities. Figure 8a demonstrates a representative platform for transient electronics.[1] The image shows a device that includes transistors, diodes, inductors, capacitors, and resistors, with interconnects and interlayer dielectrics, all on a silk film. Figure 8b shows circuit components with key materials and device structures. Mg is used as the conductor, MgO as dielectrics, monocrystalline Si as semiconductors, and silk as the substrate and packaging material. This fabrication requires the combined use of transfer printing and physical vapor deposition to make the key circuit components. Figure 8c shows the timeline of the transient electronics' dissolution in water. The whole circuit was able to dissolve in DI water within 10 min (Figure 8c). To demonstrate the biocompatibility of the constituent materials and their potential applications for biomedical implants, the transient electronic device was applied to an *in vivo* evaluation in which the device was implanted in the subdermal region of mice. As shown in Figure 8d, examination after 3 weeks exhibited only faint

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

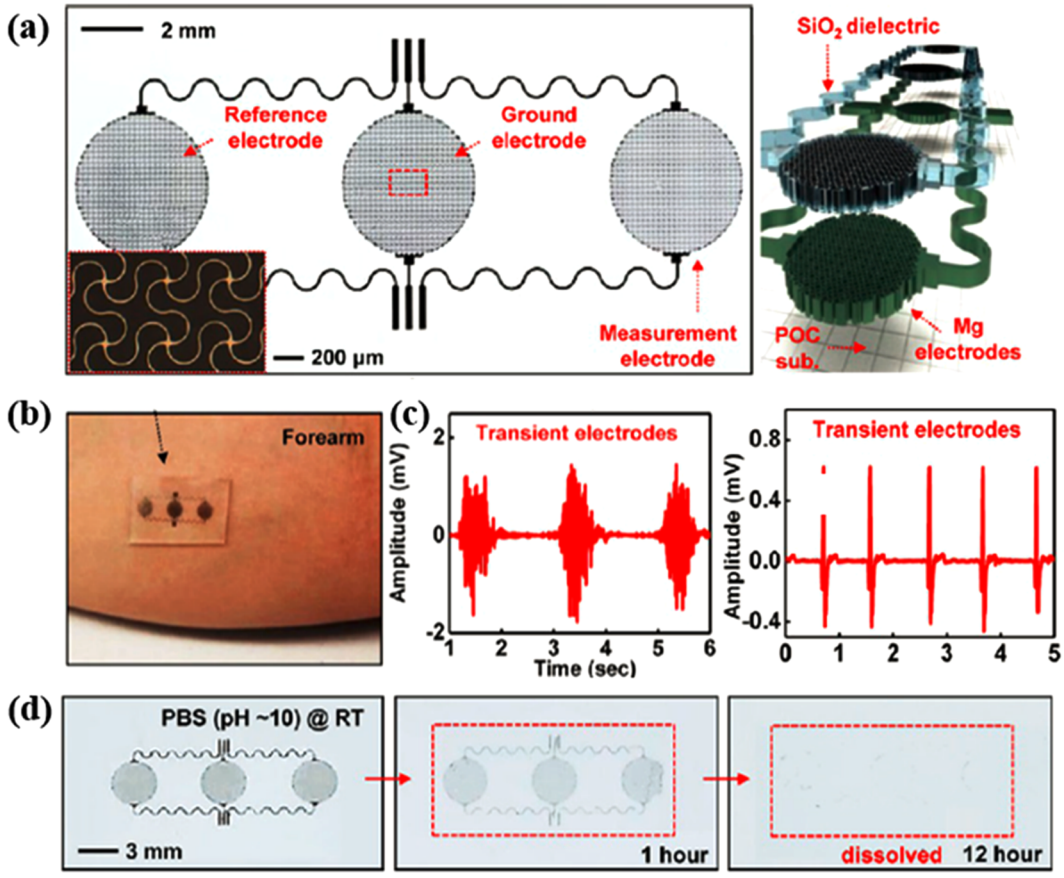


Figure 9. Biodegradable and stretchable EP sensors. (a) Optical image and schematic of a sensor (inset: magnified view of the FS mesh electrode structure). (b) Photograph of the EP sensor located on the forearm. (c) Measurement of ECG and EMG. (d) Dissolution evolution of sensor in PBS (pH = 10) at room temperature. Reprinted with permission from ref 6. Copyright 2015 American Chemical Society.

residues and slow reintegration into the subdermal layers, revealing no significant inflammatory reactions occurred.

Most of the transient electronics are designed with either a rigid or a flexible format; however, when electronics are required to integrate with the human body, a stretchable design becomes more desirable in order to respond to the mechanical deformation induced by body movement. Recently, Hwang et al.[6] developed stretchable transient, capacitive electrophysiology (EP) sensors by using biodegradable elastomers and Si nanomembranes/nanoribons. Figure 9a shows an image and a schematic of the stretchable transient EP sensor. The device contains thin layers of Mg and SiO_2 in a mesh electrode structure with ground and reference electrodes and connecting leads for measurements. The Mg electrode was attached to the skin through a sheet of stretchable polymer. A biodegradable elastomer (poly(1,8-octanediol-*co*-citrate), POC) was used as the stretchable polymer substrate. This transient EP sensor can be reversibly stretched to strains up to ~30% with a linear, elastic-mechanical response. Meanwhile, the electrical properties of this EP sensor are similar to those using nontransient constructions. The sensing mechanism relies on the displaced currents generated by capacitive coupling through the SiO_2. To evaluate the performance, electromyograms (EMG) were recorded by attaching the transient EP sensors on the forearm of a volunteer (Figure 9b). The resulting EMG data given in Figure 9c is comparable quantitatively to the data collected using conventional gel-based electrodes, indicating a high level fidelity of the EP sensor. Figure 9d shows the transient behavior in phosphate buffered solutions (PBS, pH = 10).

3.2. Transient Energy Storage. Energy storage plays a significant role in transient technology. As an important power supply, batteries are widely used in different electronic devices. It is crucial to develop transient batteries to power potential and current transient electronics to achieve fully transiency. An additional motivation of a transient design in energy storage is associated with the future management of increasingly large quantities of energy storage waste, especially those from portable electronics and electrical vehicles (EV). This concept provides a possibility to address the issues of battery recycling. If waste batteries can be transient in a relative fast and safe way, the recycling process of batteries might become easy and low-cost.

Recently, Yin et al.[14] designed a fully biodegradable, primary battery by using Mg as anode, biodegradable metals (Mo) as cathode, and biodegradable polymers (e.g., polyanhydrides) as packaging. This battery would be fully transient in biofluids and groundwater. The cells were designed in series to increase the output voltage. Figure 10a shows the schematic of the stacked configuration of four Mg−Mo cells. In the stacked configuration, a thin layer of polyanhydride acts as spacer to prevent electrical shorts between single cells and provide physical separation for the electrolytes in each chamber. The Mo powder and water-soluble polymers together provide electrical connections between individual cells. Figure 10b gives the actual battery configuration. The single Mg−Mo cell can provide a voltage of 0.45 V, and the stacked cells give a stable voltage output around 1.6 V at a constant current density (0.1 mA/cm^2) for up to 6 h. In Figure 10d, a porous thin film is used as top cover to confine the electrolyte. The transience of the battery is demonstrated in

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

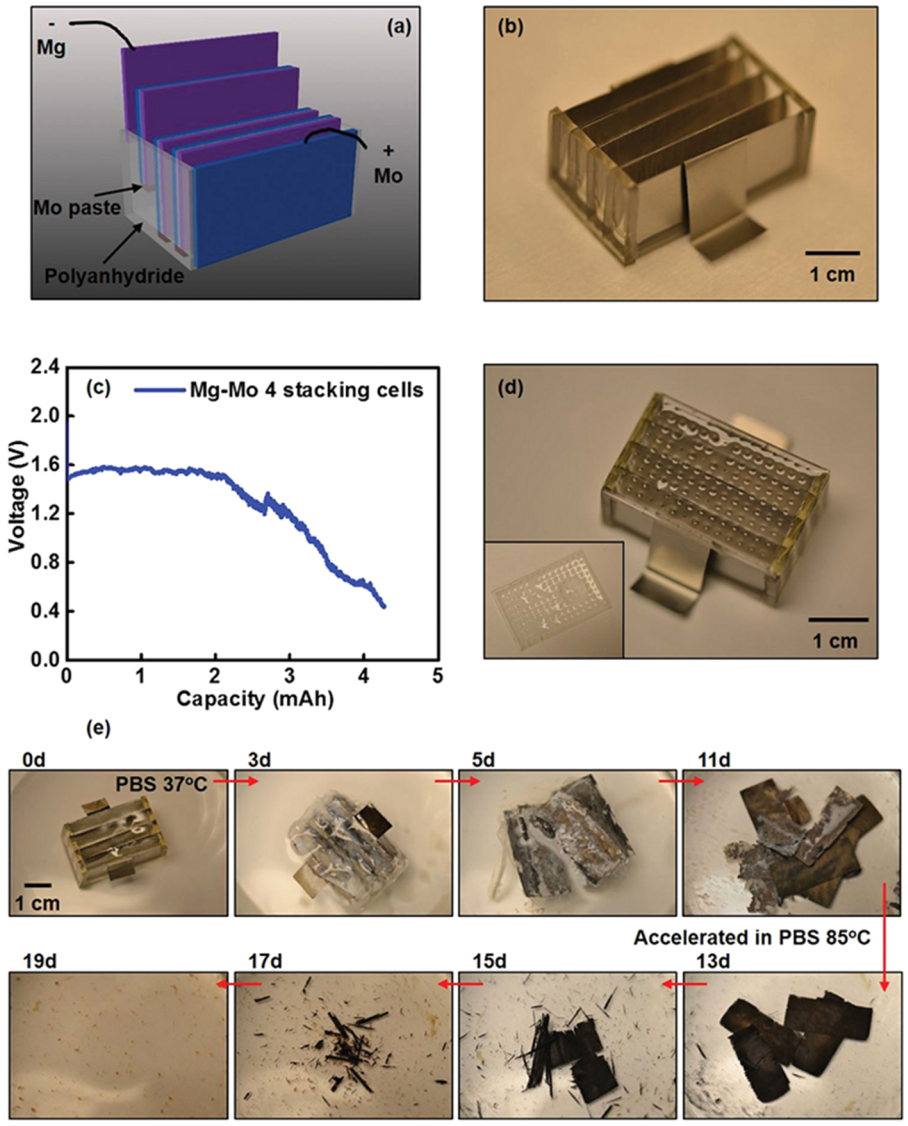


Figure 10. Transient primary battery. (a) Configuration of a battery pack that consists of four Mg−Mo cells in series. (b) Optical images of the battery. (c) Discharge profile (0.1 mA/cm^2). (d) Top porous polymer cover to confine the electrolytes. (e) Transient behavior. Reprinted with permission from ref 14. Copyright 2014 Wiley.

Figure 10e. Actually, the degradation of the battery begins once the battery is made, due to the dissoluble nature of those metals. Therefore, it is necessary to design a battery that can last for longer times and can be used multiple times, and upon being triggered, it can become transient instantly.

The transient batteries are required to obtain the following characteristics: (1) all the battery components must physically or chemically disappear, (2) they must be transient at a controllable rate, (3) they must have high battery performance, (4) they must have appropriate battery size and mass, and (5) they must have flexible design of battery that is compatible with other transient electronics. Fu et al.[16] designed for the first time rechargeable transient lithium ion batteries (LIBs). In their work, vanadium oxide (V_2O_5) was selected as the cathode due to its high theoretical capacity and working voltage, while lithium metal foil was cut into an appropriate size as the anode. In addition, polyvinylpyrrolidone (PVP) fabricated by electro-spinning served as the separator. Sodium alginate (Na-AG) film was selected as battery encasement since it is stable in conventional electrolytes but has fast transience in water-based solutions. Al metal and copper metal was deposited on the Na-AG by a shadow-mask metal deposition technique as the current collectors. The electrolyte was 1 M $LiPF_6$ in ethylene carbonate (EC)/diethyl carbonate (DEC) (1:1 vol %). The battery remained stable with the electrolyte and in an ambient environment but exhibited fast transience when triggered by water. Figure 11a presents the full disintegration and dissolution of transience of the LIB by water triggering through cascade reactions. The alginate substrate was first dissolved into the water, followed by the PVP separator dissolution. Next, the solution reacted with the Li metal anode releasing hydrogen gas and generating LiOH. The as-formed LiOH rapidly reacted with V_2O_5 cathode due to its one-dimensional nanostructure. Eventually, all the battery components disappear within a few minutes without any visible residue. Figure 11b is the optical image of a prototype of the transient battery. The battery was assembled by stacking components with controllable sizes. Such LIBs are capable of lightening an LED with a 1.6 V threshold voltage (Figure 11c). As for the electrochemical performance of this transient LIB, the battery had a working voltage of ∼2.8 V

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

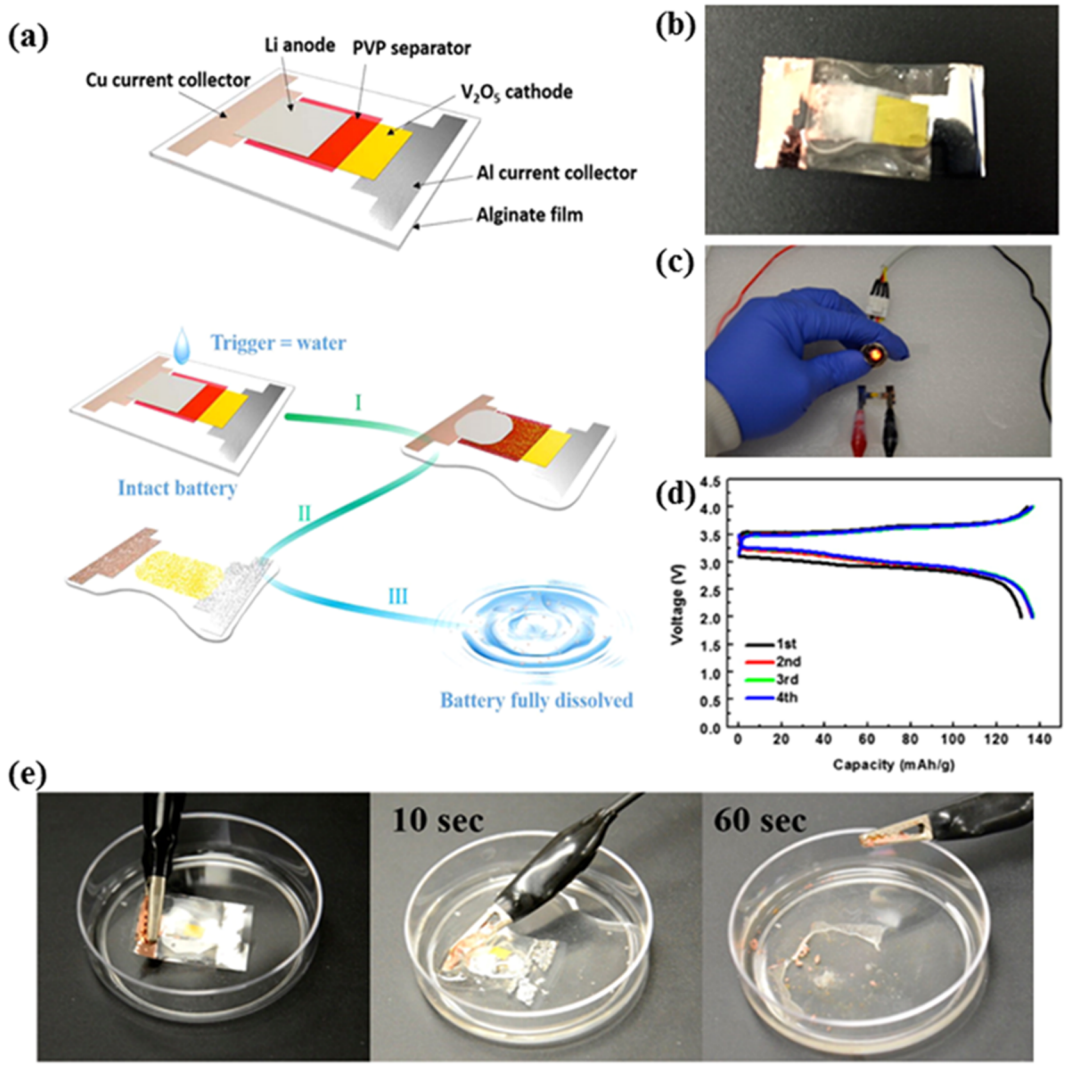


Figure 11. Transient rechargeable battery: (a) Schematic process of triggered transient battery dissolution. (b) Digital image of a single transient battery. (c) LED powered by a V_2O_5 transient battery. (d) Charge–discharge curves of the V_2O_5 transient battery. (e) Dissolution of the transient battery in water at room temperature. Reprinted with permission from ref 16. Copyright 2015 American Chemical Society.

and delivered an energy of ~0.29 mW·h as shown in Figure 11d. Additionally, this battery also displayed a great cycling performance with a high Coulombic efficiency. Figure 11e illustrates the transience cascade of the V_2O_5 battery at room temperature by water triggering. As described previously, the LIBs reacted with the transient trigger dramatically and quickly dissolved into the solution within 10 min. Even the copper current collector disintegrated into small pieces.

3.3. Conclusions and Outlook. We have briefly reviewed the recent developments of transient technology for the applications of transient electronics and energy storage by focusing on the materials, designs, and performances of those devices. A large section of this review was devoted to transient materials, covering metals, polymers, and semiconductor materials. In the transient electronics section, we reviewed recently reported electronics and their applications for biomedical and wearable functions. In the energy storage section, primary batteries and rechargeable batteries based on transient battery components and packaging were reviewed.

Further research should consider increasing the performance of the developed transient devices, which need to be comparable with conventional devices to be employed in regular use. Although there is a trade-off between device performance and transient capabilities, it is important to find an appropriate balance. However, and most importantly, the transient property should not compromise the functionalities of device. Most of the recent developments of the electronic devices focus on solutions to trigger the transience. Another research interest is the design of internal stimulus to achieve self-degradability. Once the internal material receives the "signal" from an outside stimulus, the materials, structures, and systems can respond quickly to become transient.

Inspired from the "disposal" idea, we can define a broader meaning to transient electronics, especially for the portable electronics and batteries that are featured with disposable characteristics to achieve biocompatibility, biodegradability, and environmental friendliness with the surrounding environment and human body. In the future, we believe that the transient concept, combined with advanced materials and innovated designs, will provide new insights into addressing the challenges between the environment, manufacturing, recycling, and cost. These transient technologies will open up a new era for transient devices and beyond.

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527–3539

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

AUTHOR INFORMATION

Corresponding Author

*(L.H.) E-mail: binghu@umd.edu.

Notes

The authors declare no competing financial interest.

Biographies

Kun Fu received his Bachelor's degree in Textile Science and Engineering from Donghua University (2009), Master's degree in Textile Science from Philadelphia University (2011), and Ph.D. degree in Fiber and Polymer Science from North Carolina State University (2014). He is currently a postdoctoral research associate under the supervision of Prof. Liangbing Hu in the Energy Research Center at University of Maryland, College Park. His research mainly focuses on materials, devices, and systems for advanced energy storage.

Zhengyang Wang received his Bachelor's degree in Inorganic Non Metallic Materials Engineering from Central South University (2013) and Master's degree in Material Engineering from University of Maryland College Park (2015). He was a research assistant under the supervision of Prof. Liangbing Hu in the Energy Research Center at University of Maryland, College Park (2015), and is currently a Ph.D. student in Fire Protection Engineering at University of Maryland, College Park.

Jiaqi Dai received his B.S degree in Materials Science and Engineering from Harbin Institute of Technology (2013), China. He is currently a Ph.D. candidate in materials engineering under the supervision of Prof. Liangbing Hu at University of Maryland, College Park, U.S.A. His research mainly focus on nanotechnologies, advanced energy storage devices, and scientific visualizations.

Marcus Carter completed his bachelor's studies at Frostburg State University in 2012. He is engaged in research focused on creating the next generation of battery materials by synthesizing hybrid materials toward large-scale energy storage and flexible electronics. He is pursuing his Ph.D. studies under the supervision of Prof. Liangbing Hu and Prof. Zhihong Nie in the Chemistry and Biochemistry Department at the University of Maryland, College Park.

Liangbing Hu received his B.S. in applied physics from the University of Science and Technology of China (USTC) in 2002. He did his Ph.D. at UCLA, focusing on carbon nanotube based nanoelectronics. In 2006, he joined Unidym Inc. as a cofounding scientist. At Unidym, Liangbing's role was the development of roll to-roll printed carbon nanotube transparent electrodes and device integrations into touch screens, LCDs, flexible OLEDs, and solar cells. He worked at Stanford University from 2009 to 2011, where he worked on various energy devices based on nanomaterials and nanostructures. Currently, he is an associate professor at University of Maryland College Park. His research interests include nanomaterials and nanostructures, roll-to-roll nanomanufacturing, energy storage and conversion, and printed electronics.

REFERENCES

(1) Hwang, S.-W.; Tao, H.; Kim, D.-H.; Cheng, H.; Song, J.-K.; Rill, E.; Brenckle, M. A.; Panilaitis, B.; Won, S. M.; Kim, Y.-S.; Song, Y. M.; Yu, K. J.; Ameen, A.; Li, R.; Su, Y.; Yang, M.; Kaplan, D. L.; Zakin, M. R.; Slepian, M. J.; Huang, Y.; Omenetto, F. G.; Rogers, J. A. A Physically Transient Form of Silicon Electronics. *Science* **2012**, *337*, 1640−1644.

(2) Yin, L.; Cheng, H.; Mao, S.; Haasch, R.; Liu, Y.; Xie, X.; Hwang, S. W.; Jain, H.; Kang, S. K.; Su, Y.; Li, R.; Huang, Y.; Rogers, J. A. Dissolvable Metals for Transient Electronics. *Adv. Funct. Mater.* **2014**, *24*, 645−658.

(3) Hwang, S. W.; Kim, D. H.; Tao, H.; Kim, T. i.; Kim, S.; Yu, K. J.; Panilaitis, B.; Jeong, J. W.; Song, J. K.; Omenetto, F. G.; Rogers, J. A. Materials and Fabrication Processes for Transient and Bioresorbable High-Performance Electronics. *Adv. Funct. Mater.* **2013**, *23*, 4087−4093.

(4) Huang, X.; Liu, Y.; Hwang, S. W.; Kang, S. K.; Patnaik, D.; Cortes, J. F.; Rogers, J. A. Biodegradable Materials for Multilayer Transient Printed Circuit Boards. *Adv. Mater.* **2014**, *26*, 7371−7377.

(5) Hwang, S. W.; Song, J. K.; Huang, X.; Cheng, H.; Kang, S. K.; Kim, B. H.; Kim, J. H.; Yu, S.; Huang, Y.; Rogers, J. A. High Performance Biodegradable/Transient Electronics on Biodegradable Polymers. *Adv. Mater.* **2014**, *26*, 3905−3911.

(6) Hwang, S.-W.; Lee, C. H.; Cheng, H.; Jeong, J.-W.; Kang, S.-K.; Kim, J.-H.; Shin, J.; Yang, J.; Liu, Z.; Ameer, G. A.; Huang, Y.; Rogers, J. A. Biodegradable Elastomers and Silicon Nanomembranes/Nanoribbons for Stretchable, Transient Electronics, and Biosensors. *Nano Lett.* **2015**, *15*, 2801−2808.

(7) Kang, S. K.; Hwang, S. W.; Yu, S.; Seo, J. H.; Corbin, E. A.; Shin, J.; Wie, D. S.; Bashir, R.; Ma, Z.; Rogers, J. A. Biodegradable Thin Metal Foils and Spin-On Glass Materials for Transient Electronics. *Adv. Funct. Mater.* **2015**, *25*, 1789−1797.

(8) Li, R.; Cheng, H.; Su, Y.; Hwang, S. W.; Yin, L.; Tao, H.; Brenckle, M. A.; Kim, D. H.; Omenetto, F. G.; Rogers, J. A.; Huang, Y. An analytical model of reactive diffusion for transient electronics. *Adv. Funct. Mater.* **2013**, *23*, 3106−3114.

(9) Kang, S. K.; Hwang, S. W.; Cheng, H.; Yu, S.; Kim, B. H.; Kim, J. H.; Huang, Y.; Rogers, J. A. Dissolution Behaviors and Applications of Silicon Oxides and Nitrides in Transient Electronics. *Adv. Funct. Mater.* **2014**, *24*, 4427−4434.

(10) Kang, S.-K.; Park, G.; Kim, K.; Hwang, S.-W.; Cheng, H.; Shin, J.; Chung, S.; Kim, M.; Yin, L.; Lee, J. C.; Lee, K. M.; Rogers, J. A. Dissolution Chemistry and Biocompatibility of Silicon-and Germanium-Based Semiconductors for Transient Electronics. *ACS Appl. Mater. Interfaces* **2015**, *7*, 9297−9305.

(11) Hwang, S. W.; Kang, S. K.; Huang, X.; Brenckle, M. A.; Omenetto, F. G.; Rogers, J. Materials for Programmed, Functional Transformation in Transient Electronic Systems. *Adv. Mater.* **2015**, *27*, 47−52.

(12) Lee, C. H.; Kang, S. K.; Salvatore, G. A.; Ma, Y.; Kim, B. H.; Jiang, Y.; Kim, J. S.; Yan, L.; Wie, D. S.; Banks, A.; Oh, S. J.; Feng, X.; Huang, Y.; Troester, G.; Rogers, J. A. Wireless Microfluidic Systems for Programmed, Functional Transformation of Transient Electronic Devices. *Adv. Funct. Mater.* **2015**, *25*, 5100−5106.

(13) Park, C. W.; Kang, S. K.; Hernandez, H. L.; Kaitz, J. A.; Wie, D. S.; Shin, J.; Lee, O. P.; Sottos, N. R.; Moore, J. S.; Rogers, J. A.; White, S. R. Thermally Triggered Degradation of Transient Electronic Devices. *Adv. Mater.* **2015**, *27*, 3783−3788.

(14) Yin, L.; Huang, X.; Xu, H.; Zhang, Y.; Lam, J.; Cheng, J.; Rogers, J. A. Materials, designs, and operational characteristics for fully biodegradable primary batteries. *Adv. Mater.* **2014**, *26*, 3879−3884.

(15) Dagdeviren, C.; Hwang, S. W.; Su, Y.; Kim, S.; Cheng, H.; Gur, O.; Haney, R.; Omenetto, F. G.; Huang, Y.; Rogers, J. A. Transient, biocompatible electronics and energy harvesters based on ZnO. *Small* **2013**, *9*, 3398−3404.

(16) Fu, K.; Liu, Z.; Yao, Y.; Wang, Z.; Zhao, B.; Luo, W.; Dai, J.; Lacey, S. D.; Zhou, L.; Shen, F.; Kim, M.; Swafford, L.; Sengupta, L.; Hu, L. Transient Rechargeable Batteries Triggered by Cascade Reactions. *Nano Lett.* **2015**, *15*, 4664−4671.

(17) Liu, Z.; Fu, K.; Wang, Z.; Zhu, Y.; Wan, J.; Yao, Y.; Dai, J.; Kim, M.; Swafford, L.; Wang, C.; Hu, L. Cut-and-stack nanofiber paper toward fast transient energy storage. *Inorg. Chem. Front.* **2016**, DOI: 10.1039/C5QI00288E.

(18) Fu, K. K.; Wang, Z.; Yan, C.; Liu, Z.; Yao, Y.; Dai, J.; Hitz, E.; Wang, Y.; Luo, W.; Chen, Y.; et al. All-Component Transient Lithium-Ion Batteries. *Adv. Energy Mater.* **2016**, 1502496.

(19) Bettinger, C. J.; Bao, Z. Organic Thin-Film Transistors Fabricated on Resorbable Biomaterial Substrates. *Adv. Mater.* **2010**, *22*, 651−655.

(20) Irimia-Vladu, M.; Troshin, P. A.; Reisinger, M.; Shmygleva, L.; Kanbur, Y.; Schwabegger, G.; Bodea, M.; Schwödiauer, R.; Mumyatov, A.; Fergus, J. W.; et al. Biocompatible and Biodegradable Materials for Organic Field-Effect Transistors. *Adv. Funct. Mater.* **2010**, *20*, 4069−4076.

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539

(21) Hernandez, H. L.; Kang, S. K.; Lee, O. P.; Hwang, S. W.; Kaitz, J. A.; Inci, B.; Park, C. W.; Chung, S.; Sottos, N. R.; Moore, J. S.; et al. Triggered Transience of Metastable Poly (phthalaldehyde) for Transient Electronics. *Adv. Mater.* **2014**, *26*, 7637−7642.
(22) Zeng, R.; Dietzel, W.; Witte, F.; Hort, N.; Blawert, C. Progress and challenge for magnesium alloys as biomaterials. *Adv. Eng. Mater.* **2008**, *10*, B3−B14.
(23) Witte, F. The history of biodegradable magnesium implants: a review. *Acta Biomater.* **2010**, *6*, 1680−1692.
(24) Kirkland, N.; Birbilis, N.; Staiger, M. Assessing the corrosion of biodegradable magnesium implants: a critical review of current methodologies and their limitations. *Acta Biomater.* **2012**, *8*, 925−936.
(25) Keim, S.; Brunner, J. G.; Fabry, B.; Virtanen, S. Control of magnesium corrosion and biocompatibility with biomimetic coatings. *J. Biomed. Mater. Res., Part B* **2011**, *96*, 84−90.
(26) Jin, S. H.; Shin, J.; Cho, I.-T.; Han, S. Y.; Lee, D. J.; Lee, C. H.; Lee, J.-H.; Rogers, J. A. Solution-processed single-walled carbon nanotube field effect transistors and bootstrapped inverters for disintegratable, transient electronics. *Appl. Phys. Lett.* **2014**, *105*, 013506.
(27) Acar, H.; Çınar, S.; Thunga, M.; Kessler, M. R.; Hashemi, N.; Montazami, R. Study of physically transient insulating materials as a potential platform for transient electronics and bioelectronics. *Adv. Funct. Mater.* **2014**, *24*, 4135−4143.
(28) Seo, W.; Phillips, S. T. Patterned plastics that change physical structure in response to applied chemical signals. *J. Am. Chem. Soc.* **2010**, *132*, 9234−9235.
(29) Jung, Y. H.; Chang, T.-H.; Zhang, H.; Yao, C.; Zheng, Q.; Yang, V. W.; Mi, H.; Kim, M.; Cho, S. J.; Park, D.-W.; et al. High-performance green flexible electronics based on biodegradable cellulose nanofibril paper. *Nat. Commun.* **2015**, *6*, 7170.
(30) Huang, J.; Zhu, H.; Chen, Y.; Preston, C.; Rohrbach, K.; Cumings, J.; Hu, L. Highly transparent and flexible nanopaper transistors. *ACS Nano* **2013**, *7*, 2106−2113.
(31) Zhu, H.; Xiao, Z.; Liu, D.; Li, Y.; Weadock, N. J.; Fang, Z.; Huang, J.; Hu, L. Biodegradable transparent substrates for flexible organic-light-emitting diodes. *Energy Environ. Sci.* **2013**, *6*, 2105−2111.
(32) Zhu, H.; Fang, Z.; Preston, C.; Li, Y.; Hu, L. Transparent paper: fabrications, properties, and device applications. *Energy Environ. Sci.* **2014**, *7*, 269−287.
(33) Hwang, S.-W.; Park, G.; Edwards, C.; Corbin, E. A.; Kang, S.-K.; Cheng, H.; Song, J.-K.; Kim, J.-H.; Yu, S.; Ng, J.; et al. Dissolution Chemistry and Biocompatibility of Single-Crystalline Silicon Nanomembranes and Associated Materials for Transient Electronics. *ACS Nano* **2014**, *8*, 5843−5851.

Downloaded from pubs.acs.org/cmatex/article-pdf/28/11/3527/7972298/cm5b04931.pdf by YALE UNIV user on 28 September 2026

DOI: 10.1021/acs.chemmater.5b04931
Chem. Mater. 2016, 28, 3527−3539